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DOCTORAL THESIS

Relationship of changes in strength and power characteristics to swimming start performance.

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Relationship of changes in strength and power characteristics to swimming start performance

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ABSTRACT

The overall aim of this thesis was to describe the strength and power characteristics required for swim start performance, and the effects of dry-land resistance training on the swim start. To achieve this, the thesis was broken into five research chapters.

The first study (Chapter 3) reviewed the current literature on the acute relationship between dry-land physical performance measures and swim start performance along with the acute and chronic effects of dry-land resistance training on swim start performance. A range of strength and power exercises were highly correlated to swim start performance, especially when utilising body weight vertical jumping exercises such as countermovement (CMJ) and squat jump (SJ) ($r > 0.90$). A variety of resistance training approaches were also found to significantly improve swim start performance, especially when these programs included plyometric and non-plyometric jumps.

The second study (Chapter 4) developed a multiple regression model to determine the most important SJ force-time predictors for swim start times to 5 m and 15 m in high performance male and female swimmers. Concentric impulse was identified as a key lower body force-time characteristic to start times to 5 m and 15 m in both sexes, with Reactive strength index modified and concentric mean power also contributing to start performance in female swimmers.

The third study (Chapter 5) sought to identify which block outcome kinetic measures have the greatest relationship to 15 m start time and to understand the direction and temporal sequencing of forces in the block phase. Linear mixed modelling identified four on-block outcome kinetic variables (work, average power, horizontal take-off velocity, and average acceleration) as having a very large relationship ($R^2 = 0.79$ - 0.83) to 15 m start time. On-block force sequencing started with the rear leg, followed by upper limb grab forces and the front leg.

The fourth study (Chapter 6) compared the effects of an 8-week horizontal- (HF) and vertical-force (VF) oriented emphasis resistance training program on swim start performance (HF: $n = 6$; VF: $n = 5$). While seven moderate between-group effect size differences were observed, no significant between-group differences were observed between the HF and VF groups in predicted one repetition maximum strength, SJ force-time characteristics, and swim start performance measures post-intervention.

The final study (Chapter 7) was a case series that involved longitudinal monitoring of body composition, SJ force-time characteristics and swim start performance over a competitive season (with three assessment time points over ~12 months) in five high performance swimmers. Repeated measures correlation analyses indicated a number of significant interactions between physical and technical components that can influence a swimmer's start performance in both the flight and in-water phases. However, changes in swim start performance and the other variables assessed were quite individual.

In summary, the results of this thesis have increased our understanding of the determinants of swim start performance in high performance swimmers. These findings may have relevance for how strength and conditioning coaches and sports science practitioners can best contribute to improving swim start performance in high performance swimmers.

KEYWORDS

swimming, swim start, dry-land, resistance training, strength, power

DECLARATION BY AUTHOR

This thesis is submitted to Bond University in fulfilment of the requirements of the degree of Doctor of Philosophy by Research (Health Sciences).

I, Shiqi Thng, declare that the research presented within this thesis is a product of my own original ideas and work and contains no material which has previously been submitted for a degree at this university or any other institution, except where due acknowledgement has been made.

Shiqi Thng

01 December 2020

DECLARATION OF AUTHOR CONTRIBUTIONS

Paper 1: Relationships Between Dry-land Resistance Training and Swim Start Performance and Effects of Such Training on the Swim Start: A Systematic Review

Authors	Concept & Design	Data Collection	Data Analysis	Drafting of Manuscript	Critical Revision
Shiqi Thng	50	100	75	70	60
Simon Pearson	25	-	10	10	10
Justin Keogh	25	-	15	20	30

Paper 2: The prediction of swim start performance based on squat jump force-time characteristics

Authors	Concept & Design	Data Collection	Data Analysis	Drafting of Manuscript	Critical Revision
Shiqi Thng	30	80	80	70	40
Simon Pearson	35	20	-	10	25
Evelyne Rathbone	-	-	20	5	5
Justin Keogh	35	-	-	15	30

Paper 3: On-block mechanistic determinants of start performance in high performance swimmers

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Simon Pearson	40	25	35	10	15

Lachlan Mitchell	20	25	30	-	5
Clare Meulenbroek	20	25	-	-	-
Justin Keogh	-	-	-	20	40

Paper 4: Pushing up or pushing out? An initial investigation into horizontal- versus vertical-force training on swimming start performance: A pilot study

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Shiqi Thng	35	50	50	70	35
Simon Pearson	35	50	15	5	30
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Paper 5: Longitudinal tracking of body composition, lower limb force-time characteristics and swimming start performance in high performance swimmers

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Media

I was granted the opportunity by Bond University in 2018 to give an insight into my research topic. This interview can be on the following link:

https://www.dailytelegraph.com.au/sport/commonwealth-games/commonwealth-games-2018-aussie-swimmers-secret-weapon/news-story/c09b3b605658624f9818ab43859f9ffa

ETHICS DECLARATION

The research associated with this thesis received ethics approval from Bond University Human Research Ethics Committee under reference numbers 0000016006 and 00088, The University of Queensland Human Research Ethics Committee (HMS17/41), and Swimming Australia Ltd.

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LIST OF ABBREVIATIONS

1RM	one repetition maximum
3RM	three repetition maximum
ANOVA	Analysis of variance
ANZBMS	Australian and New Zealand Bone Mineral Society
BIHS	Bond Institute of Health and Sport
BW	bodyweight
CA	conditioning activity
CI	Confidence interval
CMJ	Countermovement jump
DXA	Dual Energy X-Ray Absorptiometry
ES	effect size
EWU	arm stroke and split stance lunge on flywheel inertial device
F	females
FINA	International Swimming Federation
Fmax	leg extensor maximum voluntary force
fps	frames per second
FS	freestyle
HCMJ	horizontal countermovement jump
HF	horizontal force
hIMP	horizontal impulse
HSJ	horizontal squat jump
hSPF	starting peak horizontal force
Hz	hertz
ISAK	International Society for the Advancement of Kinanthropometry
JD	jump distance
KiSwim	Kistler Performance Analysis System for swimming
km	kilometres
km/d	kilometres per training day
KPASS	Kistler Performance Analysis System for swimming
L	loaded
LWU	split stance lunge on the Smith machine
m	metres
M	males
m/d	metres per day
m/s	metres per second
m/s^2	metres per second squared
MeSH	medical subject headings
MVIC	maximum voluntary isometric contraction
n	number
NOS	Newcastle-Ottawa Quality Assessment scale
PAP	post-activation potentiation
Pavg	average power
PEDro	Physiotherapy Evidence Database
PP	peak power
PPavgrel	average relative power
PPrel	relative peak power

PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
QAS	Queensland Academy of Sport
RMWU	arm stroke and split stance lunge on Smith machine
r_{rm}	repeated measures correlations
s	second
SA	Swimming Australia
SD	standard deviation
SJ	squat jump
sPFh	starting peak horizontal forces
sPFy	starting peak vertical forces
SPSS	Statistical Package for Social Sciences
SSC	stretch-shortening cycle
SWU	standard warm-up
T10 m	time to 10 m
T15 m	time to 15 m
T1st kick	time to first kick
T5 m	time to 5 m
TOV	take-off velocity
UL	unloaded
V10 m	average velocity from 5 m to 10 m
V5 m	average velocity at 5 m
VCMJ	vertical countermovement jump
VF	vertical force
vIMP	vertical impulse
VSJ	vertical squat jump
vSPF	starting peak vertical forces
vTOV	vertical take-off velocity
yrs	years
YWU	split stance lunge on a flywheel inertial device

CHAPTER 1: NARRATIVE REVIEW

1.1 INTRODUCTION

Competitive swimming has been part of the Olympic programme since the first modern Olympic Games in 1896 (1) and includes four different strokes: front crawl (freestyle), backstroke, breaststroke and butterfly. Competition events can range from sprint (i.e. 50 m, 100 m) to middle (i.e. 200 m, 400 m) and long distance (i.e. 800 m and 1500 m) and can take place in either a short course (25 m) or long course (50 m) pool. In shorter sprint events (e.g. 50 m sprint) that may last anywhere from 22 s to 30 s, the predominant energy systems are the high-energy phosphate and anaerobic glycolysis. For longer distance events (e.g. 400 m onwards), aerobic glycolysis is the predominant energy system (2). The ultimate criterion for a successful swimming performance is to complete the specific race distance in the shortest amount of time (3). The highest levels of competition in swimming are a long course and short course World Championship that takes place every two years, and a long-course Olympic Games held every four years. As the level of competition has increased, so has the amount of swimming-specific research and sports science support provided to high performance swimmers and coaches to improve swimmers' performance.

A major area of sports science support and emerging area of research is performance analysis, whereby objective feedback through the use of video analysis and statistical information is provided to swimmers and coaches, to inform decision-making, strategy, and planning (4). Analysis of a swimming performance can be used to break down the race into four key components: the start (time to 15 m), turn commonly measured as 7.5 m into and out of the wall (or 5 m into and 10 m out of the wall), finish (5 m into the wall on the last lap) and free swim (the portion of the race for each lap that does not include the start, turns or finish components) (5, 6).

Close margins can occur in sprint and middle distance swimming events, with winning margins as little as 0.01 s (7). As an example, at the 2016 Olympic Games, 0.01 s decided medal outcomes in the men's 50 m freestyle, 100 m butterfly and 200 m backstroke events, along with the women's 100 m freestyle, 100 m backstroke and 4x100 m medley relay. Given how close competition results can be, finding ways to improve in all four phases of competitive swimming has become increasingly important. As a result of these potentially minuscule winning margins, performance analysis data provides valuable information regarding the swimmers' relative strengths and weaknesses compared to their competitors. Specifically, data detailing the time spent in the four major components, as well as the sub-phases of these components in a real or simulated race, can be used to identify aspects of swimming performance, and therefore preparation in and out of the pool, which could be targeted to address relative weaknesses and enhance performance advantages for athletes.

1.2 SWIM START

The swim start is a separate skill compared to the free swim, turns and finish portion of a race as swimmers start completely out of the water on the starting blocks, unless competing in the backstroke event (8, 9). A start is usually defined as the time from the start signal to when a swimmer's head crosses the 15 m mark (10), which is the maximum distance that a swimmer can travel underwater before their head is required to break the surface of the water in all events other than breaststroke (11). Depending on the stroke and distance of the events, swim starts have been estimated to account for 0.8 % to 26.1 % of the overall race time, with the latter representing the percentage in a 50 m front crawl sprint event (12, 13). Although swimmers spend much less time in the swim start compared to the free swimming phase, swim starts are known to be a determining factor for success, especially in sprint distance events, as it is the part of the race when the swimmer is travelling at the highest velocity (12, 14).

Biomechanical analyses of the swim start using video and sometimes instrumented force platforms on the starting block are currently used in high performance swimming. This analysis is then used to monitor progress, track changes in performance related variables and identify the strengths and weaknesses of the swimmer (4). For example, in an evaluation of video footage of 100 m performances at the 2013 FINA World Swimming Championships by Veiga, Roig (15), it was found that the average velocities of elite swimmers from the start phase to the point of breaking out of the water was faster than subsequent free swimming velocities. This higher velocity of the swim start is due to three factors: 1) high take-off velocities off the block (approximately 4.5 – 5 m/s in elite male swimmers) in the dive phase (16); 2) lower resistance forces in the air during the dive and the utilisation of an underwater streamlined position (17); and 3) propulsion in the form of undulatory leg kicks during the underwater phase (18). The significance of these 3 factors is clear when compared to the free swimming phase, which has an average velocity of 1.8 – 2 m/s (5). Thus, any improvements within aspects of the swim start can have a major impact on overall race success. As a result, it is imperative for swimmers to maximise their velocity off the starting blocks and maintain as much of this velocity as possible throughout the first 15 m and the remainder of the race.

1.3 PHASES OF A SWIM START

Three primary phases contribute towards the overall start time: the block phase, the flight phase, and the underwater phase (12), along with an additional free swimming phase from the point of reaching the surface to the 15 m mark. The block phase requires a quick reaction to the starting signal and a large take-off velocity that is primarily horizontal in direction (19). The take-off velocity is proportional to the impulse produced on the blocks and is inversely proportional to the swimmers' body mass. As the impulse is the product of the ground reaction forces and the time of force application, the swimmer has to face an element of compromise between leaving the blocks as quickly as possible and maintaining contact long enough to generate a larger impulse and therefore higher take-off velocity. The block phase is followed by the flight phase which is the projectile motion phase in which the swimmer becomes airborne and finishes when they make contact with the water (14, 20). The third and longest phase of the swim start is the underwater phase, in which swimmers attempt to maintain a streamlined position through undulatory leg kicks with their arms outstretched in front of the head to minimise velocity loss until their head resurfaces just before the 15 m mark (8). Once the swimmer reaches the surface, they begin to commence free swimming with both arms and legs in their respective stroke while the head breaks the surface of the water. This transition between the underwater phase and the free swimming to the 15 m mark is known as the break-out (21). Taken together, for the purposes of this thesis, the underwater phase and this transition is termed as the 'in-water phase'.

The block, flight and underwater phases account for approximately 11 %, 5 % and 84 % respectively of the total start time (20). Even though a swimmer spends the highest percentage of the start in the underwater phase, the block phase is reported to have the greatest impact on the duration of the flight and subsequently the underwater phase, as all three phases are interdependent (22). Therefore, each phase of the swim start must be carefully coordinated to maximise the contribution to overall swimming performance. The following sections will provide additional detail on the block, flight, and underwater phases of the swim start.

1.3.1 BLOCK PHASE

The block phase consists of two distinct actions:

1. Reaction to the start signal
2. Impulse generated on the starting block

On the starting signal, a swimmer pulls on the block with the arms and executes a powerful lower body action involving hip extension, knee extension and plantar flexion to generate a high enough impulse to propel themselves forward (23). To optimise block performance, the reaction and movement time needs to be as short as possible while still allowing the swimmer to produce a sufficiently high impulse on the starting block and horizontal take-off velocity (24, 25). The compromise between block time and horizontal take-off velocity reflects the impulse-momentum relationship, whereby an impulse (the product of force and time of force application) needs to be generated to cause a change in momentum (i.e., the product of mass and velocity). With respect to swim starts, this means there needs to be sufficient time on the block for the swimmer to generate high forces to maximise initial horizontal take-off velocity (26). A possible strategy to increase impulse generated on the start blocks without excessively increasing the time of force application, is to increase muscular strength and power (especially of the lower body) and ensure the appropriate sequencing of joint movements during the dive action (10).

1.3.1.1 Evolution of swim starts

Biomechanical research on the swim start has been conducted to identify the most effective start technique for performance. Such research has focused on comparing several alternative block start techniques to improve start performance. Prior to 2008, two styles of swim start techniques were commonly used: the grab start, and the track start. The primary difference between these techniques was the foot placement on the blocks. For example, in the grab start, both feet were positioned parallel to the front of the starting block, with the toes curled over the front edge (27). In the track start, one foot was placed on the front of the starting block while the other foot was placed to the rear (28). Regardless of these swim start techniques, swim start performance will be influenced by the laws of projectile motion in which the speed, angle and height of release are all important factors.

1.3.1.2 Introduction of OSB11 start block

In 2008, Omega released a new starting block called the OSB11 (20), which features an adjustable kick plate slanted at a fixed angle of 30° which can be placed in one of five different positions, each at a set distance (35 mm intervals) along the length of the starting platform (Figure 1-1). This starting block was first authorised for competition on January 1st 2010 (26). The swim start technique used on the OSB11 block is referred to as the kick start.

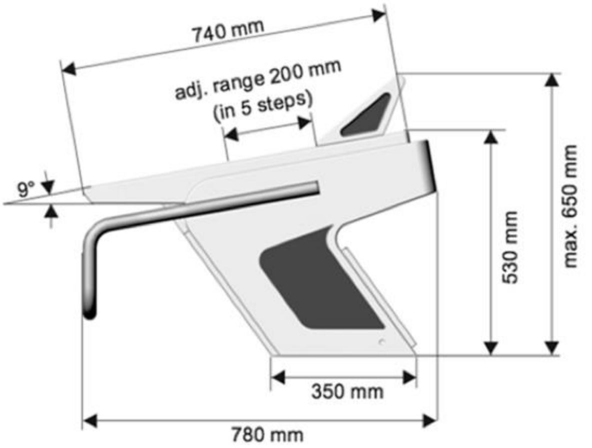

Figure 1-1. OSB11 starting block (OMEGA, Switzerland)

Several researchers have described the swimming kick start to be similar to a track and field sprint start in terms of foot placement, whereby both the swimming kick start and the track and field start require an initial rear leg drive followed by a front leg drive (29). When performing the kick start, the rear foot is positioned on the adjustable kick plate, with the front foot positioned on the front plate. The rationale for this design was that the kick plate may allow for an increased duration of effective force application (i.e. greater horizontal force component) on the blocks, which in turn increases horizontal impulse and the horizontal take-off velocity. Honda et al. (30) have also identified that the kick plate on the OSB11 start block is capable of significantly improving both time to 5 m and 7.5 m, with a further 0.04 s improvement obtained in the kick start compared to the track start technique. This is attributed to an increase in horizontal force production and ultimately take-off velocity that is able to be produced by the rear leg on the kick plate (30).

1.3.2 FLIGHT PHASE

The flight phase follows the block phase, and is defined as the time from when the swimmer's front toe leaves the block until the first water contact with either the finger tips (31), or the apex of the head (32). As velocity is defined as speed in a given direction, any change in the magnitude or direction of the resultant velocity of the swimmer's centre of mass during the flight phase may have an effect on the time to 5 m and 15 m. Cossor, Mason (12) observed a significant negative correlation between flight distance and start time in the women's 200 m individual medley and the 400 m freestyle events (*r* = -0.67 and -0.94, respectively) at the Sydney 2000 Olympic Games. The authors concluded that the further the distance attained in the flight phase, the quicker the time to 15 m. In an analysis of the phases of the swim start by

Ruschel et al. (33), the same trend was observed, with greater flight distances corresponding to a faster time to 15 m. The increase in flight distance was primarily determined by a higher horizontal take-off velocity.

1.3.3 UNDERWATER PHASE

The underwater phase is defined as the period of time from when the apex of the swimmer's head enters the water to when it breaks the surface of the water and the swimmer commences free swimming (32). Upon water entry, swimmers obtain and hold a streamlined position to reduce hydrodynamic drag and initiate undulatory leg kicks in order to maintain as much of the entry velocity as possible before beginning free swimming (9, 17). Previous research has highlighted the importance of the underwater phase as it is when the swimmer is travelling at their fastest through the water (25, 32, 34). As the free swim velocity is a function of the preceding velocity obtained in the underwater phase, ensuring minimum loss in velocity during the underwater-to-free swim transition is crucial (35). Therefore, the average velocity during the underwater phase of the swim start is highly dependent on the horizontal velocity at entry and the drag forces acting on the swimmer (32).

1.3.4 SUMMARY OF THE SWIM START

Overall, the swim start is a discrete skill comprising of many sub-phases. In order to optimise horizontal impulse and take-off velocity in the block phase, high levels of technical ability and coordination, combined with the physical capacity to produce sufficiently large and effectively coordinated forces to the block through the hands and feet are required. Further, minimising the time to 15 m also requires a clean entry into the water and a streamlined glide position with undulatory leg kicks to minimise velocity loss while transitioning into the break-out of full swimming and stroking after 15 m (26).

Previous research has indicated that one of the key factors in start performance is generating a high horizontal take-off velocity from the block. To be able to achieve a high take-off velocity, the swimmer needs to be able to apply a large horizontal impulse (force multiplied by time of force application) to the blocks. Assuming that the body mass of two swimmers is equal, the swimmer that can produce a greater horizontal impulse on the blocks would have a greater horizontal take-off velocity, which in turn allows them to travel further horizontally in the air before entering the water. On this basis, Miller et al. (7) were some of the first researchers to suggest that strength (resistance) training focusing on lower limb extensor muscles would assist in generating a greater impulse during the time the swimmer is in contact with the blocks.

In the following section, an examination of the role of muscular strength and power (sometimes referred to as force-time) characteristics for swimming is presented. This section will initially focus on the free swimming phase to better contextualise the current strength and conditioning practices within the sport of swimming.

1.4 IMPORTANCE OF MUSCULAR STRENGTH AND POWER FOR SWIMMING PERFORMANCE

As swim start performance is determined by the ability of the swimmer to produce a high level impulse from zero velocity, muscular strength, rate of force development and power may be three determining factors for successful performance in competitive swimming, particularly in sprint distances, since high free swim velocities are observed in these events (36). While swim training is predominantly used to elicit the aerobic and anaerobic physiological adaptations for the sport, swim training alone may not be sufficient to optimally develop the muscular strength, rate of force development and power required, especially for sprint swimmers. The majority of propulsive forces in the free swim phase comes from the upper body, with the latissimus dorsi and pectoralis major being considered the main propulsive muscles in the pull phase of a swim stroke (37, 38). In terms of the role of the lower body, leg kicks supply approximately 31 % of the total force produced during sprint swimming (3). It has also been proposed that the major role of the lower body during the free swim is to act as a stabiliser that maintains a streamlined position to reduce drag forces (1).

Several investigations (39-41) have demonstrated large to almost perfect relationships between tethered forces and swimming performance. For example, large correlations ($r = 0.61$) have been shown between peak forces in tethered swimming with 200 m freestyle swimming performance (40), with peak forces having very large relationships to 50 m and 100 m freestyle performance ($r = -0.82$, $r = -0.74$, respectively) (41). Almost perfect correlations between peak forces ($r = 0.91$) per stroke with 50 m freestyle swimming times have also been observed (39), suggesting that neuromuscular abilities (i.e. maximum muscle strength and power) are a highly significant factor in determining swimming performance, especially over sprint distances.

As shown in Figure 1-2, two main strategies that can be used to develop muscular strength, rate of force development and power capabilities in swimmers are dry-land resistance training and in-water resistance training (1, 42). A recent systematic review of the current evidence suggests that a lower volume (low number of total sets and repetitions), high intensity (high velocity/ force) dry-land resistance training program using conventional gym-based resistance training exercises was most effective for an optimal transfer to free swimming performance. Such a result was attributed to this form of exercise prescription inducing less neuromuscular fatigue while at the same time producing greater strength and neuromuscular improvements than higher volume training programs (42). However, Crowley and colleagues (42) only reviewed dry-land resistance training studies on free swimming performance and specifically excluded swim starts in their systematic review. As such, further research should be undertaken to investigate the impact of dry-land resistance training on swim start performance.

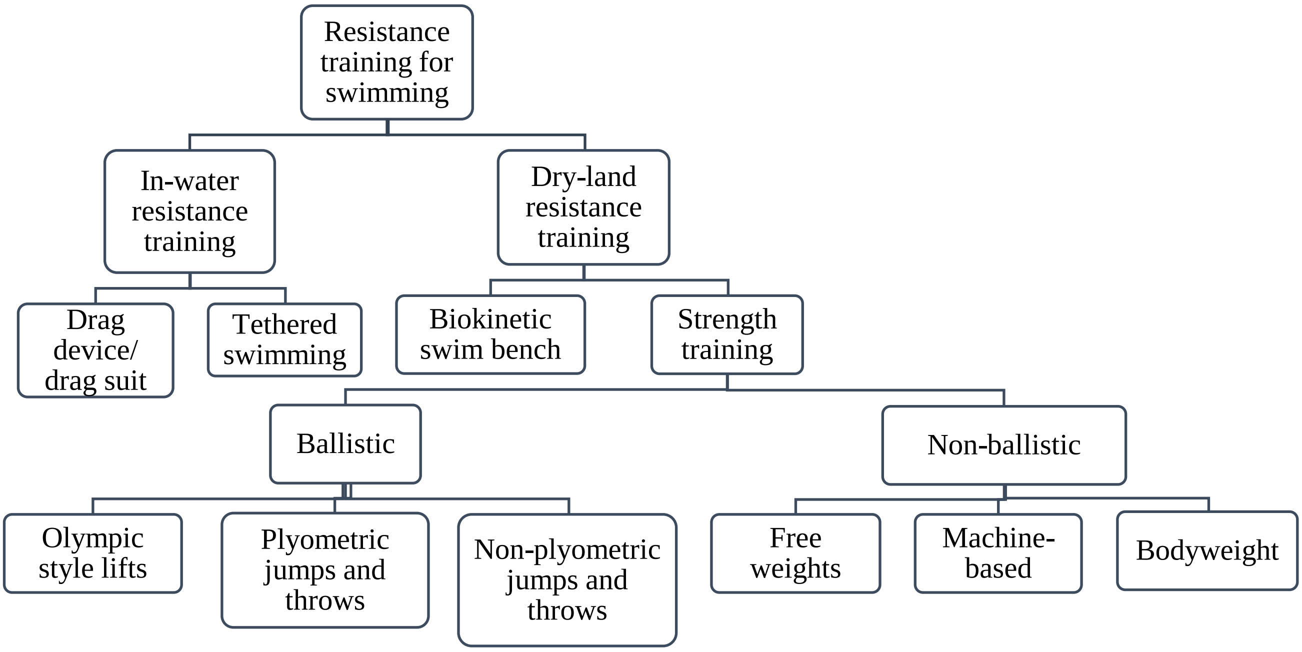

Figure 1-2. Resistance training modalities used in competitive swimming.

1.5 CONCURRENT TRAINING: IMPLICATIONS FOR THE DEVELOPMENT OF NEUROMUSCULAR ABILITIES FOR THE SWIM START

As discussed previously, there appears to be reasonable evidence indicating that incorporating a dry-land resistance training program into an overall swimming program leads to greater improvements in swimming performance than swim training alone (1, 42). The simultaneous integration of swim training and dry-land resistance training within a periodised program is referred to as concurrent training (43). The question that then arises is what constitutes the balance of concurrent training for an optimal development of muscular strength and power as well as maximal aerobic and anaerobic endurance capacity in swimmers (44, 45).

There is complexity in concurrent training in that both swim training and resistance training impose different acute stresses on the body that may elicit distinct adaptations (46). In particular, the concurrent development of both muscular strength and power from resistance training, and aerobic and anaerobic endurance from swimming training can lead to conflicting neuromuscular adaptations (47). Competitive swimmers often engage in up to nine or ten in-water pool sessions weekly, with sessions typically lasting around two hours each. Raglin et al. (48) reported training loads during a competitive swim season may range from 5 km per training day (km/d) during the general training phase, 8.3 km/d during peak training and as low as 2.3 km/d during the taper period. However, some athletes can have training volumes as high as 16 km/d (> 100 km/week) in peak training. In comparison, dry-land resistance training is generally performed a maximum of three times a week, totalling between three to five hours weekly (49). Thus, with such high swim training loads, it is inevitable for some form of same day concurrent training to happen.

1.6 LONGITUDINAL MONITORING STUDIES IN SWIMMING

Due to the nature of elite sports, proper planning and periodisation of training program variables such as intensity, frequency and volume of exercise are necessary to maximise physical and physiological adaptations and to avoid overtraining in athletes (45). Seasonal trends and individual variability in performance may occur during different time points of the season, depending on the competition and periodisation plans and goals of the swimmer, swim coach, and strength and conditioning coach. Thus, analysis of these trends may provide an understanding of possible factors that contribute to changes in swim start performance and strength and power characteristics. This can assist strength and conditioning coaches and swim coaches in making informed decisions for the preparation of annual plans and training programs for upcoming seasons.

In the swimming literature, current research on long-term tracking (generally over one to two years) appears to have focused on swimming biomechanics, such as stroke length and stroke rates, physiological variables such as lactate and VO_2max and monitoring changes in body composition across seasons (49-51). For example, analysis of swimming performance in 40 elite swimmers showed a ~2 % increase in swimming speed within a season, with these progressions between seasons getting smaller each year (51). In a two-year study looking to identify physiological and biomechanical factors contributing to competition performance in nine competitive male swimmers, at least two consecutive seasons were required to observe a slight improvement in performance (50). The small degree of improvement within and between seasons may be indicative of the challenges presented with highly trained, high performance athletes in making substantial performance improvements over a one to two-year period. In contrast, longitudinal studies of strength and power characteristic in swimming is still relatively uncommon, although some research has examined the combined effects of resistance training and swim training across periods of 8 – 12 weeks (42), but none over the long-term.

Longitudinal studies of strength and power characteristics across any high performance sport are still relatively uncommon, although some research has examined gymnastics and various rugby codes (52-54). Argus et al. (52) reported a relative maintenance of upper body strength (-1.2 %) and a small increase in lower body strength (+8.5 %), while both upper and lower body power decreased (-3.4 %, -3.3 %) over the course of a 13-week provincial rugby union season. In a longer-term study, Appleby et al. (53) observed increases in maximal upper body and lower body strength (6.5 % – 11.5 %) in professional rugby union athletes, with the magnitude of improvement negatively associated with baseline strength levels over the two-year period. In contrast, an increase in peak power output in the SJ and CMJ (43 % and 36 %, respectively) was observed over a 3-year tracking study in NCAA division I collegiate female gymnasts (54) . While such results provide some insight into the strength and power changes likely to be observed in high-performance strength/power athletes over extended periods, it is less understood whether such changes would be of a similar magnitude in the sport of swimming, which differs substantially in their metabolic requirements and training practices. Further, at this stage, there appear to be no such longitudinal studies that have monitored changes in swimmers' body composition, strength and power characteristics and/or swim start performance, nor to examine how changes in their body composition, and strength and power characteristics can contribute to changes in swim start performance. Thus, longitudinal monitoring of body composition and a variety of dry-land strength and power characteristics as well as swim start kinematic and kinetic outputs would provide additional information relevant to improving swim starts and possibly overall swimming performance.

1.7 RATIONALE OF PROPOSED RESEARCH

While the majority of swimming sport science research has concentrated on the free swim portion, the importance of the swim start for sprint swimming event is becoming more widely recognised. The important role that muscular strength and power play in enhancing swimming performance has led to the addition of dry-land resistance training modalities into a concurrent training model for competitive swimmers. While the lower body is heavily utilised in the start phase, turn phase and leg kicks, the majority of the research into the importance of muscular strength and power has been conducted on the upper body, as these muscle groups provide the majority of the propulsive forces required for the free swimming component. As the swim start requires the lower body musculature to effectively initiate movement off the blocks, it is apparent that the development of high levels of lower body muscular strength and power is necessary to enhance this component of swim start performance. Given that winning margins can be as little as 0.01 s in competitive swimming, any improvements made in the swim start can have positive implications on overall swimming performance, especially in sprint distance events at an elite level. While there is now a reasonable amount of research published regarding factors influencing start performance, several gaps still exist in the literature, which limit their application to improving swim starts in high performance swimmers. Specifically, there are still considerable gaps in knowledge about what constitutes the most important lower body force-time and on-block kinematic/kinetic characteristics for swim start performance in high performance swimmers, and how this may change as a consequence of concurrent swimming and dry-land resistance training.

1.8 OBJECTIVES

The overall objective of this program of research is to investigate the muscular strength and power characteristics pertinent to swim start performance and to examine whether a variety of dry-land resistance training exercises positively influences swim start performance in high performance swimmers.

Within the context of this PhD thesis, “swim start performance” will encapsulate two levels of measures. The first level of analysis comprises direct performance measures of the swim start, which are the times to 5 m, and 15 m, both of which are routinely provided in standard swimming performance analysis. The second level of investigation includes the kinetic and kinematic outputs of the swim start obtained from an instrumented starting block (e.g. Kistler Performance Analysis System for swimming; Kistler Winterthur, Switzerland). This instrumented starting block was earlier called KPAS-S but underwent a name change to KiSwim in 2020. To ensure consistency within the overall thesis and published manuscripts, Chapter 4, which was accepted for publication prior to 2020, uses the name KPAS-S. This performance analysis system is referred to as KiSwim the other experimental chapters (Chapters 5, 6, and 7) in this thesis.

1.9 OVERALL AIM OF THESIS

The two primary aims of this thesis are 1) To identify the key lower body force-time characteristics and on-block kinematic and kinetic variables related to swim start performance and 2) To investigate how changes in these characteristics resulting from concurrent swimming and dry-land resistance training may influence swim start performance.

1.10 RESEARCH QUESTIONS

To achieve the stated aims, a series of research questions were developed.

Gaining an understanding of which kinematic and kinetic outputs from a variety of dry-land resistance training exercises are most related to swim start performance allows for the appropriate resistance training exercise prescription and selection of muscular strength and power assessments. Thus, the first research questions were formulated:

a) **i) What strength and power characteristics are most highly correlated to swim start performance?**

   ii) What is the acute and chronic effect of dry-land resistance training on swim start performance?

These two interrelated questions were assessed using a systematic review methodology. The primary results of this review were:

- Performance in a range of lower body strength and power exercises is highly correlated to swim start performance. Correlations appeared greatest when utilising bodyweight (BW) vertical jumping exercises, in particular the SJ ($r > 0.90$).
- Post-activation potentiation (PAP) produces significant acute improvements in swim start performance.
- Ballistic training i.e. plyometrics and non-plyometric jumps as a form of dry-land training can produce significant chronic improvements in swim start performance.

Major limitations of the previous literature summarised in the systematic review included the relatively low number of high performance swimmers, especially females, in each of the studies; the use of correlational rather than regression analysis; and the lack of research using the

OSB11 start block and the kick start technique currently used in competitive swimming. These limitations led to the formation of the second research question:

b) **What key lower body force-time characteristics in the SJ are associated with swim start performance in male and female swimmers?**

While the results of the systematic review suggested that several force-time characteristics derived from the SJ were more highly correlated to swim start performance than other lower body strength and power measures, there is no current consensus on what are the most appropriate biomechanical outputs from dry-land exercises that best predict swim start performance in high performance swimmers. Therefore, this second study sought to access a larger sample of high performance male and female swimmers and to utilise regression analyses involving a larger number of SJ outputs than has been previously used in the literature.

While developing these force-time characteristics may be achieved through appropriate dry-land resistance training programs, it was also acknowledged that swimmers need to know how to apply these characteristics on the starting blocks to improve swim start performance. With this in mind, the third research question was developed:

c) **What are the key mechanistic on-block determinants of swim start performance?**

The investigation of on-block kinetic determinants revealed the direction and temporal specificity of horizontal force application on the starting block, with the rear leg having the highest contribution to block performance. There may be a potential specificity involved in the direction of force application in dry-land resistance training exercises, which can be referred to as the force-vector theory. In a review by Randell et al. (55) on the specificity of resistance training to sports performance, it was proposed training adaptations may be direction-specific, and that athletes who are required to apply forces in the horizontal plane should perform several exercises containing a horizontal component. Within the swimming literature, previous studies (19, 56) utilising exercises that were primarily horizontal in direction provided some support for the force-vector theory in improving swim start performance. However, the aforementioned studies (19, 56) did not use the OSB11 start block nor the kick start technique that is currently used in competitive swimming. Further, the results of the systematic review in the first study also highlighted the lack of evidence on dry-land resistance training with free weights for improving swim start performance. Given that swimmers simultaneously perform swim training and dry-land resistance training within a periodised program to develop muscular strength and power capabilities (1, 42), it is imperative to compare the potential benefits of different dry-land resistance training approaches on swim start performance. This led to the development of the fourth research question:

d) **What would be the effects of a horizontal-force oriented emphasis training program on swim start performance in comparison to a vertical-force oriented emphasis training program?**

This fourth study was performed to provide greater insights into the potential direction of force application specificity of resistance training for improving swim start performance. In conjunction with the previous study that sought to determine the most important force-time characteristics in the block phase of the swim start, the results of the fourth study have the potential to inform strength and conditioning, and biomechanical assessments focused on improving swim start performance in high performance swimmers. However, a limitation of this fourth study and much of the training study literature was the short duration of training programs and the relative lack of change that would likely occur in competitive and high performance swimmers over these timeframes. This limitation led to the formation of the final research question that was addressed in the fifth study:

e) **How do body composition, lower body force-time and swim start performance characteristics change and interrelate over the course of one year?**

To date, there appear to be no longitudinal studies done within the swimming literature that have monitored changes in body composition, lower body force-time characteristics and/or swim start performance, and how these characteristics interrelate over the course of a year. Given that the concurrent training performed by high performance swimmers may elicit conflicting neuromuscular adaptations (47), longitudinal monitoring of body composition, lower body force-time characteristics, and swim start kinematic and kinetic outputs would provide additional information relevant to improving swim starts.

These five research questions provide the direction to this program of work. A pictorial overview of the overall thesis structure is shown in Figure 1-3. Specific investigations were conducted to address each of these questions and achieve the aim of this thesis.

RELATIONSHIP OF CHANGES IN STRENGTH AND POWER CHARACTERISTICS TO SWIMMING START PERFORMANCE

Chapter One: Narrative Review

Chapter Two: Methodology Overview

Chapter Three (Study 1): Relationships Between Dry-land Resistance Training and Swim Start Performance and Effects of Such Training on the Swim Start: A Systematic Review

Chapter Four (Study 2) : The Prediction of Swim Start Performance Based on Squat Jump Force-time Characteristics

Chapter Five (Study 3): On-Block Mechanistic Determinants of Start Performance in High Performance Swimmers

Chapter Six (Study 4): Pushing up or pushing out – an initial investigation into horizontal- versus vertical-force training on swimming start performance: A pilot study

Chapter Seven (Study 5): Longitudinal tracking of body composition, lower limb force-time characteristics and swimming start performance in high-performance swimmers

Chapter Eight: Discussion and Conclusion

Figure 1-3. Thesis overview.

CHAPTER 2: METHODOLOGY OVERVIEW

2.1 METHODOLOGY OVERVIEW

This chapter seeks to provide an overview of the overall methodology used throughout the thesis and some rationale for these decisions. To maximise the ecological validity of this PhD and its potential to improve swim starts in high performance swimmers, performance data was collected from as many swimmers as possible between 2016 to 2019. While most of this data was collected by the PhD candidate, a portion of this data was also collected by other Queensland Academy of Sport (QAS) and Swimming Australia (SA) staff.

Participants in all studies were informed of the nature and risks of the study before providing written informed consent using the forms presented in Appendices 1 and 3. Elite level swimmers recruited for Chapters 4 and 5 comprised of swimmers who had competed internationally in either the Olympics, Commonwealth Games or World Championships, and provided informed written consent via their SA Swimmer Agreement (Appendix 4). Due to the logistical challenges in conducting a training intervention with elite swimmers who were preparing for Commonwealth Games and/or World Championships in 2018, the participants for the training study (Chapter 6) were recruited locally. Participants recruited to the study described in Chapter 6 were national level swimmers with at least four years' experience in competing in national championships and at least one year of land-based resistance training experience under the supervision of a strength and conditioning coach.

All performance data for this project was collected at QAS, with squat jumps (SJ) for Chapters 4, 6, and 7 performed in the QAS gymnasium and swim starts for Chapters 4 to 7 performed in the QAS Sports Recovery Centre in Brisbane, Queensland, Australia. The training intervention study (Chapter 6) was conducted in the gymnasium at Bond Institute of Health and Sport (BIHS) under the supervision of the PhD candidate and at another gymnasium under the supervision of an Australian Strength and Conditioning Association Professional Coach.

Participants in the studies described in this thesis typically performed a testing session that included a lower body force-time characteristic assessment (SJ test) and the swim start performance test. Each testing session typically lasted for 1 – 2 hours. The first half hour involved performance of the SJ test in the gymnasium. After a 30-minute rest, participants then performed the swim start performance test. In study five (Chapter 7), an additional body composition assessment using a Dual Energy X-Ray Absorptiometry (DXA) scan was conducted to assess changes in total body lean mass, fat mass and segmental body composition over the course of a year. Details of the test conducted for data collection for this PhD thesis are provided below. As the details provided below were consistent with those provided in the experimental chapters (Chapters 4 to 7), there will be some redundancy with the additional details in the current chapter and that of the methods sections of the experimental chapters.

2.1.1 LOWER BODY FORCE-TIME CHARACTERISTIC ASSESSMENT USING THE SQUAT JUMP

Findings in the systematic review (Chapter 3) informed the decision to select the bodyweight (BW) SJ exercise as the lower body force-time assessment in this thesis. Specifically, swim start performance was near perfectly related ($r > 0.90$) to vertical BW jumps (countermovement jump (CMJ) and SJ) rather than measures of maximal muscle strength. Due to the concentric nature of the set-up in the block phase of the swim start, the SJ was selected rather than the CMJ.

Prior to the SJ test, participants completed a dynamic lower body warm-up under the supervision of a strength and conditioning coach. Following the warm-up, participants were given two practice jumps before the test was conducted. Jumps were performed on a force platform (ForceDecks FD4000, London, United Kingdom), with a sample rate of 1000 Hz. Participants started in an upright standing position with their hands on their hips. They were then instructed to adopt a squat position using a self-selected depth that was held for 3 s before they attempted to jump as high as possible (57). A self-selected squat depth was chosen as it has been reported to produce the greatest jump height and higher peak force outputs in comparison to measured squat depths (58). A successful trial was one that did not display any small amplitude countermovement at the start of the jump phase on the force trace (59). All participants were asked to perform three maximal intensity SJ with a 30-second passive rest in between each effort. The SJ trial with the highest jump height was kept for data analysis. Ground reaction force data from the SJs were analysed using the commercially available ForceDecks software (ForceDecks, London, United Kingdom). The software detects the initiation of movement in the squat jump when the vertical force output exceeds 20 N above body mass and the propulsive phase as the movement when the vertical forces was 30 N below body mass. Out of the variables provided by ForceDecks, 46 variables, excluding any left-to right asymmetry variables were initially extracted for use in further analysis. Descriptions of the SJ variables are provided in Appendix 8.

2.1.2 SWIM START PERFORMANCE TEST

Swim start performance were collected in the QAS Sports Recovery Centre which houses a four lane 25 m pool. Swim start performance were collected using a Kistler Performance Analysis System - Swimming (KiSwim, Kistler Winterthur, Switzerland), which utilises a force instrumented starting block, constructed to match the dimensions of the Omega OSB11 block (KiSwim Type 9691A1; Kistler Winterthur, Switzerland). Time to 5 m and 15 m were collected using five calibrated high-speed digital cameras collecting at 100 frames per second, synchronised to the KiSwim instrumented starting block. One camera was positioned 0.95 m above the water and 2.5 m perpendicular to the direction of travel to capture the start and entry of swimmer into the water, while the other three cameras were positioned 1.3 m underwater at 5 m, 10 m and 15 m perpendicular to the swimmer to capture the time to 5 m and 15 m (Figure 2-1). The times to 5 m and 15 m were defined as the time elapsed from the starting signal until the apex of the swimmers' head passed the respective distances (60). The start with the fastest time to 15 m was selected for further analysis. An Infinity Start System (Colorado Time Systems, Loveland, Colorado, USA) provided an audible starting signal to the athletes as well as an electronic start trigger to the KiSwim system.

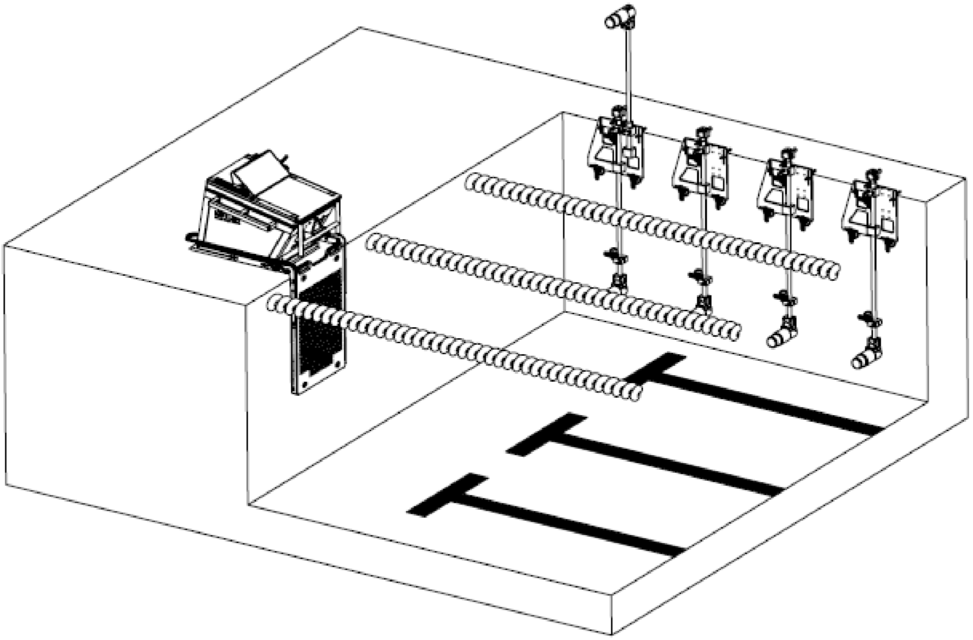

Figure 2-1. Overview of the camera set-up and the KiSwim instrumented starting block (Kistler Group, 2019) Reproduced with permission from Kistler Instrumente AG, Winterthur, Switzerland.

2.1.3 BODY COMPOSITION ASSESSMENT

DXA scans for body composition assessment in Chapter 7 was conducted at BIHS. Participants arrived to BIHS well-rested, fasted overnight, with their bladders voided before their scheduled DXA scan. Participants were instructed to present in a euhydrated state and hydration status was determined by assessing the specific gravity of the first void urine sample using a refractometer (PEN-Urine S. G., Atago, Tokyo, Japan). Upon arrival, participants underwent standing height and body mass measurements prior to the DXA scan. Stretch stature was measured as per the International Society for the Advancement of Kinanthropometry (ISAK) protocol during a maximal inhalation using a medical stadiometer (Harpenden, Hotain Limited, Crymuych, UK) to the nearest 0.1 cm. Body mass was measured using an electronic medical scale (WM202, Wedderburn, Bilinga, Australia). All participants wore minimal clothing (males: i.e., swimming trunks; females: unwired sports bra and cycling shorts) and removed all metal objects from their bodies and clothes prior to the scan.

The DXA scan was performed using a narrow angle fan beam Lunar Prodigy DXA machine (GE Healthcare, Madison, WI, USA) using the Nana positioning protocol, which has been reported as the best practice protocol in athletic population by Nana et al. (61). Previous DXA test-retest reliability of Nana positioning protocol in our laboratory had an intraclass correlation coefficient values of 0.97 – 1.00 and standard error of measurement percentage of 0.2 – 3.3 % (62). One trained technician conducted and analysed all scans to minimise any inter-tester variation. The results of the DXA scans were analysed using the GE enCORE 2016 software (version 14.10.022) as outlined by the Australian and New Zealand Bone Mineral Society (ANZBMS). Body composition outcome measures that were reported include total body mass, total body lean mass and total body fat mass, and segmental body composition results of lean mass of both legs.

CHAPTER 3: RELATIONSHIPS BETWEEN DRY-LAND RESISTANCE TRAINING AND SWIM START PERFORMANCE AND EFFECTS OF SUCH TRAINING ON THE SWIM START: A SYSTEMATIC REVIEW

3.1 PREFACE

The purpose of this chapter was to review the current literature on the relationship between dry-land resistance training and the effects of such training on swim start performance. This systematic review highlights the assessment and training modalities currently used in the literature, while addressing methodological considerations and strength diagnostics. The findings of this systematic review have direct applications to strength and conditioning coaches and sport science practitioners in two ways. Firstly, findings from the cross-sectional studies identified which lower body strength and power tests, as well as outcome measures from these tests, were most highly correlated to swim start times to 5 m and 15 m. These findings need to be considered when determining what outcomes should be routinely assessed in the long-term monitoring of high performance swimmers. Secondly, the intervention studies provided some preliminary insight into what may constitute the most important exercise prescription variables required to produce an acute or chronic improvement in swim start performance.

This chapter was published in Sports Medicine and is formatted according to the journal guidelines. A copy of the published manuscript is included in Appendix 5. Reprinted with permission from Springer Nature and the Copyright Clearance Center: Springer Nature, Sports Medicine, **Thng, S.**, Pearson, S. & Keogh, J.W.L. Relationships Between Dry-land Resistance Training and Swim Start Performance and Effects of Such Training on the Swim Start: A Systematic Review. © Springer Nature (2019).

3.2 ABSTRACT

Background: The swim start requires an explosive muscular response of the lower body musculature to effectively initiate movement off the starting blocks. There are currently key gaps in the literature evaluating the relationships between, and the effects of dry-land resistance training, on swim start performance, as assessed by the time to 5, 10 or 15 m.

Objective: The aims of this systematic review are to critically appraise the current literature on (1) the acute relationship between dry-land resistance training and swim start performance; (2) the acute and chronic effects of dry-land resistance training on swim start performance.

Methods: An electronic search using AusportMed, Embase, Medline (Ovid), SPORTDiscus and Web of Science was performed. The methodological quality of the studies was evaluated using the Newcastle-Ottawa Quality Assessment (NOS) scale (cross-sectional studies) and the Physiotherapy Evidence Database (PEDro) scale (intervention studies).

Results: Sixteen studies met the eligibility criteria, although the majority did not utilise the starting blocks or technique currently used in elite swimming. Swim start performance was near perfectly related ($r > 0.90$) to vertical bodyweight jumps and jump height. Post-activation potentiation and plyometrics were found to produce significant improvements in acute and chronic swim start performance, respectively.

Conclusion: While there appears to be strong evidence supporting the use of plyometric exercises such as vertical jumps for monitoring and improving swim start performance, future studies need to replicate these findings using current starting blocks and techniques and compare the chronic effects of a variety of resistance training programs.

Key Points

- Performance in a range of lower body strength and power exercises are highly correlated to swim start performance with correlations appearing greatest when utilising body weight vertical jumping exercises
- Post-activation potentiation can produce significant acute improvements in swim start performance
- Plyometrics as a form of dry-land training can produce significant chronic improvements in swim start performance

3.3 INTRODUCTION

A competitive swimming event can be divided into four components: the start, free swimming, turn (except for a 50 m event) and finish (5). The swim start is a separate skill compared to the free swim portion of a race, as swimmers initiate the movement on the starting block above the water for all strokes, except those competing in the backstroke event (8, 9). Swim start is defined as the time from the starting signal to when the swimmer crosses the 15 m mark in a race (10), with 15 m being the maximum distance that a swimmer can travel underwater before their head is required to break the surface of the water in all strokes except for breaststroke (11). Depending on the stroke and distances of the events, swim starts have been estimated to account for 0.8 % to 26.1 % of the overall race time, with the latter representing the percentage in a 50 m sprint front crawl (freestyle) event (12, 13).

Three primary phases contribute towards the overall start time: the block phase, flight phase and underwater phase (12, 20). A pictorial representation of the contribution of these phases, their biomechanical and anthropometric determinants is presented in Figure 3-1. The block phase requires a quick reaction to the starting signal and a large take-off velocity that has a take-off angle that is primarily horizontal in direction. The block phase is followed by the flight phase, which is the projectile motion phase in which the swimmer becomes airborne and finishes when they make contact with the water (14, 20). The underwater phase comes next, in which swimmers attempt to maintain a streamlined position through undulatory (butterfly) leg kicks with their arms outstretched in front of the head to minimise velocity loss until their head resurfaces just before the 15 m mark (8). The average velocity in the start phase has been shown to be more than twice the velocity of the subsequent free swim phase (16, 17). As a result, it is imperative for swimmers to maximise their velocity off the starting blocks and to maintain as much of this velocity throughout the 15 m start phase and into the remainder of the race. Key parameters from each phase that have been previously investigated as potential correlates or predictors of starting performance include: time on the start block, the force the swimmer produces during the block phase, take-off velocity, angle of entry into the water, velocity at entry, time spent underwater and underwater velocity (12, 32, 63).

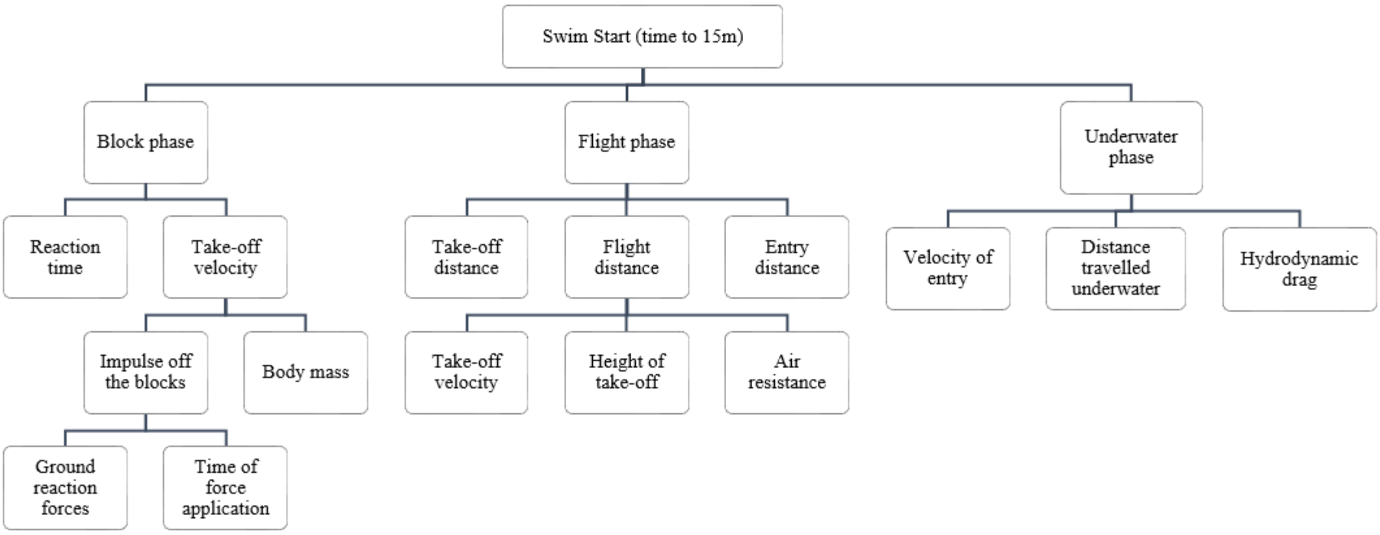

Figure 3-1. Deterministic model of the swim start.

Biomechanical research on swim start has been conducted to identify the most effective block start technique for performance. Such research has focused on comparing a number of alternative block start techniques in an attempt to improve start performance. Prior to 2008, two styles of on-block swim start techniques were most commonly used: the grab, and the track start. The primary difference between these start techniques are the foot placement on the blocks. In the grab start, both feet are positioned parallel to the front of the starting block, with the toes curled over the front edge of the starting block (27). In the track start, one foot is placed on the front of the starting block while the other foot is placed behind (28). The OSB11 start block (OMEGA, Zurich, Switzerland), which was introduced in 2010, features an adjustable kick plate slanted at a fixed angle of 30° that can be moved to five different positions, each at a set distance of 35 mm (20). A kick start technique was adopted by swimmers as a result of the addition of the adjustable kick plate, where the rear foot is elevated on the angled kick plate compared to the track start technique used previously (32). The rationale for this design was that the additional kick plate may allow for an increased duration of effective force application (i.e. greater horizontal force component) on the blocks, which in turn increases horizontal impulse and the horizontal velocity at take-off (30).

The swim start requires an explosive muscular response, especially of the lower body musculature, with swimmers having to apply large forces rapidly on the start block to increase net impulse and maximise take-off velocity in the desired direction (19). Dry-land resistance training is commonly implemented with swim training to increase lower body strength and power output. The greater the impulse (force multiplied by time of force application) produced on the start block, the greater the change in the momentum (mass multiplied by velocity) of the swimmer. Based on this relationship, the swimmer has two distinct challenges. First, is to maximise the resultant impulse while ensuring the time spent on the start block is not exceedingly long. Secondly, any increase in the force production capacity of the swimmer needs to be achieved with some minimisation of the hypertrophic response, as an increase in body mass will reduce the take-off velocity at a given impulse off the start block (Figure 3-1).

There are key gaps in the literature evaluating the relationship between dry-land resistance training and its effects on swim start performance. A recently published systematic review examined 14 studies on resistance training in swimming, but only addressed the effects on the free swim portion of a race (42). Gaining a clearer understanding of which kinematic and/or kinetic outputs from a variety of dry-land resistance training exercises are most related to swim start performance, as well as what dry-land resistance training programs are most effective in improving swim start performance, may have major implications for high-performance swim programs. Thus, the aim of this systematic review was to critically appraise the current peer-reviewed literature on 1) the acute relationship between dry-land physical performance measures and swim start performance; 2) the acute effects of dry-land resistance training on swim start performance; and 3) the chronic effects of dry-land resistance training on swim start performance.

3.4 METHODS

3.4.1 SEARCH STRATEGY

This systematic review followed the guidelines provided in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement (64). A comprehensive search of five electronic databases (AusportMed, Embase, Medline (Ovid), SPORTDiscus and Web of Science) was conducted in 02 August 2018. The University Faculty librarian assisted in the development of the search strategy. A combination of the following search terms were used: “swimming”, “start”, “strength”, “power” and “resistance training”. A comprehensive database search strategy is provided in Appendix 6.

3.4.2 SELECTION CRITERIA

After removal of duplicate studies, all study titles and abstracts were screened by two independent reviewers. Eligible articles were retrieved in full-text and evaluated for eligibility by the same two reviewers using the following criteria: (1) articles published in peer-reviewed journals, (2) journal articles with outcome measures related to the swim start. Exclusion criteria were: (1) studies that were not written in English, (2) studies that were not available in full text, (3) not an original research study, (4) a conference abstract or presentation, (5) not swimming athletes (e.g. water polo, diving, triathlon), (6) study did not measure the swim start, (7) exercises not performed on land (8) swim start not performed on the starting block (i.e. backstroke start). Reference lists of these articles were also scanned for potentially relevant articles that were not identified in the initial database search.

3.4.3 QUALITY ASSESSMENT

The quality of studies included in the review was evaluated by two independent reviewers, with differences resolved by consensus or through a third reviewer if required.

For the cross-sectional studies, the quality of studies was assessed using a modification of the Newcastle-Ottawa Quality Assessment scale (NOS) for cohort studies (65). This scale has been utilised in systematic reviews of athletes (66-68) and has been recommended by the Cochrane Handbook for Systematic Reviews of Interventions for assessing methodological quality or risk of bias in non-randomised studies (69). As follow-up for cross-sectional studies in our review was not required (item 8 on the NOS scale), we omitted that criterion in the third category and had a maximum score of 4, 2 and 2 allocated for each respective category for a total possible score of 8. The threshold used to qualitatively assess the correlations in the cross-sectional studies was based on Hopkins (70) using the following criteria: < 0.1, trivial; 0.1-0.3, small; 0.3-0.5, moderate; 0.5-0.7, large; 0.7-0.9 very large, > 0.9, nearly perfect.

For intervention studies, the Physiotherapy Evidence Database (PEDro) scale (71) was applied to assess the methodological quality of the literature. The PEDro scale is an 11-item scale that rates randomised controlled trials from 0 to 10, with 1 point given if the study satisfies the criteria and 0 points if not. Studies scoring 9-10 on the PEDro scale are considered methodologically excellent, 6-8 are considered good quality, 4-5 are considered fair and those studies scoring < 4 are considered methodologically poor.

3.5 RESULTS

3.5.1 STUDY CHARACTERISTICS AND METHODOLOGY

A total of 3369 articles were retrieved from database searches. Of the 65 studies retained for full-text screening, sixteen studies were identified for review. Out of the sixteen studies, eight were cross-sectional studies and eight were intervention studies. Of the intervention studies, four examined acute and four examined chronic outcomes. The results of the search process are illustrated in a flowchart shown in Figure 3-2.

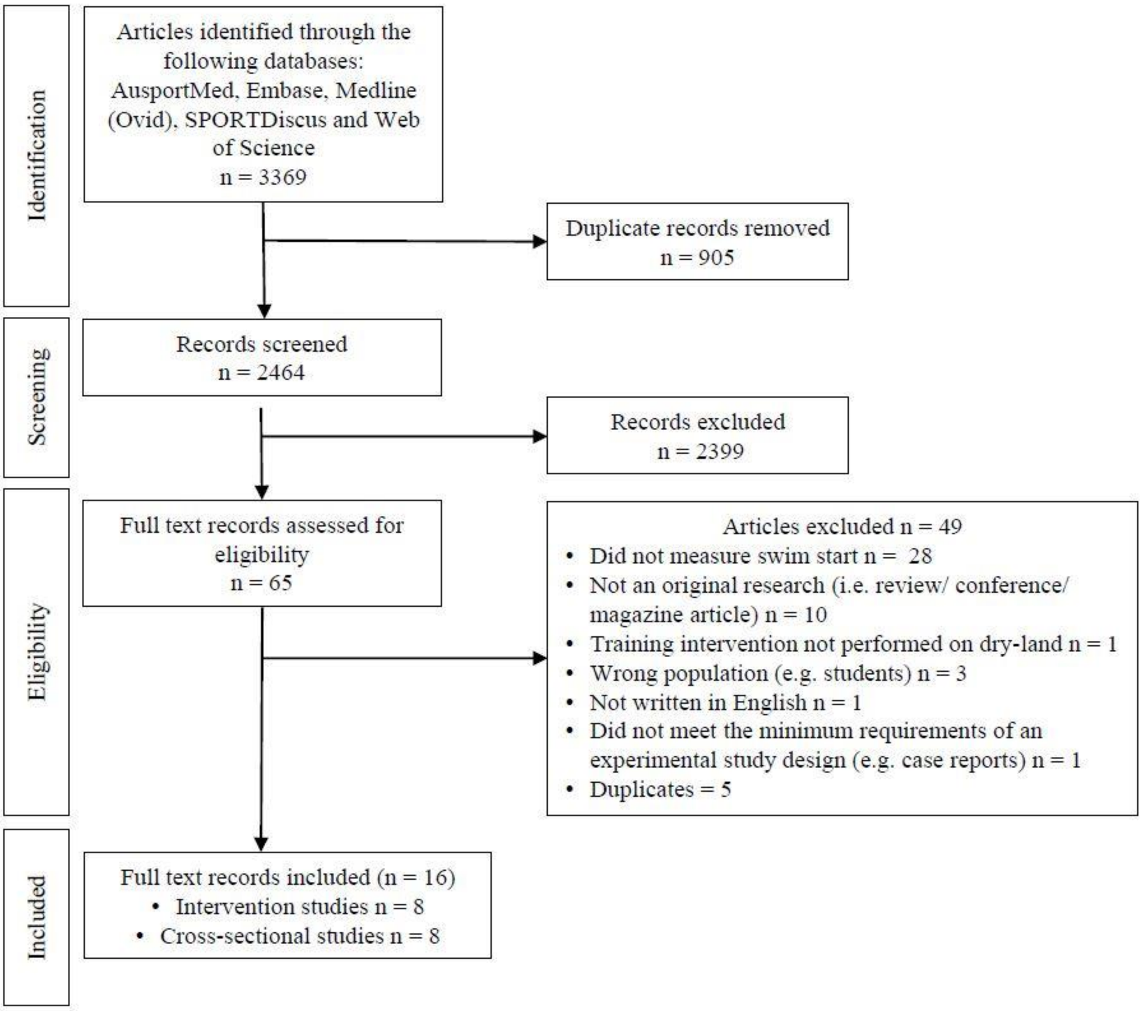

Figure 3-2. Flowchart illustrating the search process according to the PRISMA guidelines.

3.5.2 CROSS-SECTIONAL STUDIES

Results from the NOS are shown in Table 3-1, with each study having a score between 4 and 8 of a possible 8. Table 3-2 summarises the number of participants, sex, age, anthropometric characteristics, dry-land and swim start tests performed and primary kinematic/kinetic swim start outcomes in each cross-sectional study. Out of the eight studies, four studies reported using the front crawl technique (10, 72-74), while the other studies did not report the swimming stroke used in the study.

Table 3-1. Quality of the reviewed studies according to the Newcastle Ottawa Scale (NOS) for cohort studies.

Reference	**NOS score**								
	Selection				Comparability	Outcome			Total score (out of 8)
	Item 1	Item 2	Item 3	Item 4	Item 5^{a}	Item 6	Item 7	Item 8	
Benjanuvatra et al. (73)	1	1	1	1	2	0	N/A	1	7
Beretic et al. (75)	1	1	1	1	2	0		1	7
Garcia-Ramos et al. (72)	1	1	1	1	2	1		1	8
Pupišová & Pupiš (76)	1	1	0	0	1	0		1	4
Garcia-Ramos et al. (77)	1	1	1	0	2	1		1	7
Đurović et al. (78)	1	1	1	1	2	0		1	7
Keiner et al. (74)	1	1	1	0	1	0		1	5
West et al. (10)	1	1	1	0	2	0		1	6
Mean									6

Notes: 0 = no; 1 = yes; Item 1: representativeness of the exposed cohort; Item 2: selection of the non-exposed cohort; Item 3: ascertainment of exposure; Item 4: demonstration that outcome of interest was not present at start of study; Item 5: comparability of cohorts on the basis of the design or analysis; Item 6: assessment of outcome; Item 7: was follow-up long enough for outcomes to occur; Item 8: adequacy of follow up of cohorts; N/A = not applicable

[a]Maximum of 2 points can be given to item 5

Table 3-2. Summary of participant background and methodology used in the included cross-sectional studies.

Reference	**Participants** **Sex**	**Age (years)** **Anthropometrics** **(mean ± SD)**	**Dry-land exercises tested**	**Swim start test**	**Measured swim start key performance variables (units)**
Grab start					
Benjanuvatra et al. **(73)**	9 elite and 7 recreational level swimmers (F)	Elite: 19 ± 1.3 yrs 1.67 ± 0.06 m 65.5 ± 10.4 kg Recreational: 22 ± 3.1 yrs 1.69 ± 0.07 m 57.5 ± 5.9 kg	CMJ: 6 x vertical CMJ, 6 x horizontal CMJ SJ: 6 x vertical SJ, 6 x horizontal SJ	1 x maximal effort swim to 25 m	T5 m, T10 m (s) TOV (m/s) Reaction time (s) Movement time (s) Total time spent on blocks (s) hIMP, vIMP (N/kg)
Track start					
Beretic et al. **(75)**	27 international level swimmers (M)	21.1 ± 4.3 yrs 1.89 ± 10.3 m 81.6 ± 8.4 kg	2 x 5 s leg extension MVIC at 1000 Hz	Best of 3 x swim starts to 10 m	T10 m (s)
Garcia-Ramos et al. **(72)**	20 international level swimmers (F)	15.3 ± 1.6 yrs 1.67 ± 0.06 m 57.2 ± 7.4 kg	3 x CMJ 3 x SJ 2 x loaded SJ 25, 50, 75, 100 % BW each on Smith machine 2 x progressive and 2 x explosive leg extension and flexion MVIC	1 x swim start to distance slightly further than 15 m under competition rules	T5 m, T10 m, T15 m (s)
Kick start					
Garcia-Ramos et al. **(77)**[a]	15 national and international level swimmers (M)	17.1 ± 0.8 yrs 1.81 ± 0.07 m 74.1 ± 8.0 kg	2 x unloaded SJ with 0.5kg bar Loaded SJ at 25, 50, 75, 100 % BW on Smith machine	1 x swim start, using only undulatory kicks to distance slightly further than 15 m	T5 m, T10 m, T15 m (s)
Đurović et al. **(78)**	27 national level swimmers (M)	20.1 ± 3.4 yrs 1.82 ± 0.06 m 73.5 ± 7.3 kg	5 x SJ	Best of 2 x swim starts to 10 m	T10 m (s)
Keiner et al. **(74)**	21 regional level swimmers (12 M, 9 F)	17.5 ± 2.0 yrs 1.77 ± 0.10 m 69.5 ± 11.4 kg	SJ CMJ 1RM back squat 1RM deadlift	1 x maximal effort swim to 25 m under competition rules	T15 m (s)
West et al. **(10)**	11 international level swimmers (M)	21.3 ± 1.7 yrs 1.80 ± 0.10 m 78.1 ± 11.2 kg	3 x CMJ 3RM back squat	2 x swim start to distance slightly further than 15 m under competition rules	T15 m (s) hSPF (N), vSPF (N)

1RM = one repetition maximum; 3RM = three repetition maximum; BW = bodyweight; CMJ = countermovement jump; F = females; hIMP = horizontal impulse; hSPF = starting peak horizontal forces; M = males; MVIC = maximum voluntary isometric contraction; SD = standard deviation; SJ = squat jump; T5 m = Time to 5 metres; T10 m = Time to 10 metres; T15 m = Time to 15 metres; TOV = take-off velocity; vIMP = vertical impulse; vSPF = starting peak vertical forces; vTOV = vertical take-off velocity; [a]Only sea level data were included

Among the kinematic or kinetic outputs derived from the lower body strength/power tests, it appears that jump height and the take-off velocity obtained in the bodyweight (BW) CMJ and SJ had the greatest correlation with time to 5 m (73) and time to 15 m (74) out of all eight studies (Table 3-3). Pupišová & Pupiš (76) included both grab and track starts and reported a moderate (*r* = 0.59) and large correlation (*r* = 0.78) of the vertical take-off velocity in the vertical jump to swim start time to 7 m and 9 m respectively. It was unclear in the methodology of the study if any arm swing or countermovement was performed during the vertical jump.

Several studies have also examined the relationship between loaded vertical jumps and swim start performance. Peak bar velocities and jump heights from loaded SJ at four loads (25 %, 50 %, 75 % and 100 % BW) had large to very large correlation with start times to 5 m, 10 m and 15 m for international female (72) and male swimmers (77). With respect to lower body maximal and submaximal strength assessments, a very strong relationship with aspects of swim start performance was observed in the two studies that included the back squat (10, 74) (Table 3-3).

Table 3-3. Summary of the results indicating the relationship between dry-land exercises and swim start performance.

Reference	Correlated dry-land exercises	Correlated dry-land key performance variables (units)	Dry-land exercise correlation to swim start performance measures				
			T5 m	T10 m	T15 m	sPFh	sPFv
Grab start							
Benjanuvatra et al. (73)	VCMJ	VCMJ-JH (cm)	r = -0.96**				
T5m: (recreational only)		VCMJ-TOV (m/s)	r = -0.95**				
T15m: (elite only)	VSJ	VSJ-JH (cm)	r = -0.92**				
		VSJ-TOV (m/s)	r = -0.91**				
	HCMJ	HCMJ-TOV (m/s)	r = -0.86*				
	HSJ	HSJ-TOV (m/s)	r = -0.86*				
		HSJ-JD (cm)			r = -0.72*		
Track start							
Beretic et al. (75)	Leg extension MVIC	F_{rel} (N/kg)		r = -0.73***			
		F_{max} (N)		r = - 0.56*			
Garcia-Ramos et al. (72)	BW-CMJ	CMJ-TOV (m/s)	r = -0.62**	r = -0.49*			
	BW-CMJ	CMJ- PP_{rel} (W/kg)	r = -0.61**	r = -0.55*			
	BW-SJ	SJ-TOV (m/s)	r = -0.56*				
	BW-SJ	SJ-PP_{rel} (W/kg)	r = -0.57**				
	L-SJ at 25, 50, 75, 100 % BW	BV (m/s)	BV at 50 % BW r = -0.72**	BV at 75 % BW r= -0.59**	BV at 75 %BW r= -0.68**		
			BV at 25 %BW r = -0.66**	BV at 25 % BW r = -0.57**	BV at 100 %BW r= -0.64**		
			BV at 75 %BW r= -0.63**	BV at 50 % BW r = -0.57**	BV at 25 %BW r = -0.63**		
			BV at 100 %BW r= -0.57*	BV at 100 % BW r= -0.50*	BV at 50 %BW r = -0.63**		
		PP_{rel} (W/kg)	PP_{rel} at 50 %BW r = -0.63**	PP_{rel} at 25 %BW r = -0.55*	PP_{rel} at 75 % BW r= -0.64**		
			PP_{rel} at 25 %BW r = -0.62**	PP_{rel} at 75 %BW r= -0.54*	PP_{rel} at 100 %BW r= -0.64**		
			PP_{rel} at 75 %BW r= -0.57**	PP_{rel} at 50 %BW r = -0.51*	PP_{rel} at 25 %BW r = -0.57**		
			PP_{rel} at 100 %BW r= -0.54*	PP_{rel} at 100 %BW r= -0.47*	PP_{rel} at 50 %BW r = -0.54*		
		PP (W)		PP at 25 %BW r = -0.49*	PP at 25 % BW r = -0.49*		
Kick start							
Garcia-Ramos et al. (77)[a]	UL-SJ with 0.5 kg bar	JH (cm)	UL-JH r = -0.55*	UL-JH r = -0.77**	JH at 75 % BW r= -0.72**		
	L-SJ at 25, 50, 75, 100 % BW		JH at 50 % BW r = -0.53*	JH at 75 % BW r= -0.73**	JH at 100 % BW r= -0.70**		
			JH at 25 % BW r = -0.52*	JH at 25 % BW r = -0.68**	UL-JH r = -0.67**		
				JH at 100 % BW r= -0.68**	JH at 25 % BW r = -0.58*		
				JH at 50 % BW r = -0.65**			
Start technique not stated							
Đurović et al. (78)	BW-SJ	PP (W)		r = -0.39*			
		P_{avg} (W)		r = -0.43*			
		F_{max} (N)		r = -0.42*			
		PP_{rel} (W/kg)		r = -0.55*			
		PP_{avgrel} (W/kg)		r = -0.59*			
		F_{rel} (N/kg)		r = -0.64**			
Keiner et al. (74)	BW-SJ	JH (cm)			r = -0.94*		
	BW-CMJ	JH (cm)			r = -0.92*		
	1RM back squat	1RM back squat (kg)			r = -0.76*		
	1RM deadlift	1RM deadlift (kg)			r = -0.68*		
West et al. (10)	BW-CMJ	PP (W)			r = -0.85**	r = 0.87**	
		JH (cm)			r = -0.69*	r = 0.73*	r = 0.78**
		PP_{rel} (W/kg)			r = -0.66*	r = 0.78**	r = 0.79**
	3RM back squat	Estimated 1RM back squat (kg)			r = -0.74**	r = 0.71*	r = 0.62*

1RM = one repetition maximum; 3RM = three repetition maximum; BV = bar velocity; BW = bodyweight; CMJ = countermovement jump; Fmax = leg extensor maximum voluntary force; Frel = leg extensor relative maximum voluntary force; JD = jump distance; HCMJ = horizontal countermovement jump; HSJ = horizontal squat jump; JH = jump height; L = loaded; MVIC = maximum voluntary isometric contraction; Pavg = average power; PPavgrel = average relative power; PP = peak power; PPrel = relative peak power; SJ = squat jump; sPFh = starting peak horizontal forces; sPFv = starting peak vertical forces; TOV = take-off velocity; UL = unloaded; VCMJ = vertical countermovement jump; VSJ = vertical squat jump; $p < 0.05$*; $p < 0.01$**; $p < 0.001$***

[a]Only sea level data were included; values for each study are listed from highest to lowest correlation

3.5.3 INTERVENTION STUDIES

PEDro scores for the eight intervention studies ranged from 4 to 6 out of a maximum 11 (Table 3-4). Table 3-5 provides an overview of the acute training interventions, which includes trunk activation exercises (79) and post-activation potentiation (PAP) (80-82), while Table 3-6 provides an overview of the chronic training interventions, which includes plyometric training (19, 56, 83) and lower body resistance training exercises (84). Out of the eight intervention studies identified, only one study (83) utilised a controlled trial design with an intervention and control group; the remaining seven studies utilised an uncontrolled pre- and post-test design (Table 3-5 and 3-6). The two main statistical methods used in the included intervention studies were a repeated measures analysis of variance (ANOVA) and paired T-test.

Table 3-4. Quality of the included intervention studies as assessed on the Physiotherapy evidence database (PEDro) scale.

Reference	**PEDro scores**										
	Item 1	Item 2	Item 3	Item 4	Item 5	Item 6	Item 7	Item 8	Item 9	Item 10	Item 11	Total score (out of 11)
Acute interventions												
Iizuka et al. (79)	0	0	0	0	0	0	0	1	1	1	1	4
Cuenca-Fernandez et al. (82)	1	1	0	0	0	0	0	1	1	1	0	5
Cuenca-Fernandez et al. (81)	1	1	0	0	0	0	0	1	1	1	1	6
Kilduff et al. (80)	1	1	0	0	0	0	0	1	1	1	0	5
Chronic interventions												
Bishop et al. (83)	1	1	0	0	0	0	0	1	1	1	0	5
Garcia-Ramos et al. (84)	0	0	0	0	0	0	0	1	1	1	1	4
Rebutini et al. (19)	1	0	0	0	0	0	0	1	1	1	0	4
Rejman et al. (56)	1	0	0	0	0	0	0	1	1	1	0	4
Mean												5

Notes: 0 = item not satisfied; 1 = item is satisfied; Item 1 = eligibility criteria were specified; Item 2: subjects were randomly allocated to groups; Item 3: allocation was concealed; Item 4: the groups were similar at baseline regarding the most important prognostic indicators; Item 5: there was blinding of all subjects; Item 6: there was blinding of all therapists who administered the therapy; Item 7: there was blinding of all assessors who measured at least one key outcome; Item 8: measures of at least one key outcome were obtained from more than 85% of the subjects initially allocated to groups; Item 9: all subjects for whom outcome measures were available received the treatment or control condition as allocated or, where this was not the case, data for at least one key outcome was analysed by “intention to treat”; Item 10: the results of between-group statistical comparisons are reported for at least one key outcome; Item 11: the study provides both point measures and measures of variability for at least one key outcome

Seven of the eight studies demonstrated that the participants showed within-group improvements in a number of kinematic and kinetic characteristics of swim start performance (Table 3-5 and 3-6, respectively). Iizuka et al. (79) observed a 2.3 % improvement in swim time to 5 m and a 5.6 % improvement in the average velocity from 0 – 5 m as a result of an acute trunk exercises that sought to activate deep trunk muscles such as the transverse abdominis and the internal obliques on swim start performance in 9 elite level swimmers (Table 3-5). All three studies that investigated the acute effects of PAP on swim start performance (80-82) demonstrated significant improvements in swim start performance (Table 3-5).

In the four chronic intervention studies, a number of significant improvements in swim start performance were observed in all three studies involving plyometric training (Table 3-6). All three studies demonstrated within group improvements in take-off velocity (19, 56, 83) and horizontal take-off velocity (19). Likewise with swim start kinematic measures, Rejman et al. (56) and Bishop et al. (83) reported a quicker swim start time to 5 m and 5.5 m (-7.5 % and -15.2 % respectively) post plyometric training intervention (Table 3-6). In contrast, Garcia-Ramos et al. (84) observed decrements in 13 international level swimmers' swim start performance (time to 10 m: +2.3 %; time to 15 m: +3.9 % respectively) after a three-week sea level training camp prior to an altitude training camp. Although the study's primary aim was to quantify the effects of an altitude training camp on swimming start performance, the participants performed a sea level training camp for three weeks prior to the altitude training camp. To allow a more direct comparison of the study by Garcia-Ramos et al. (84) with the current literature, the data presented in this section relate to their sea level training camp.

Table 3-5. Summary of participant background, methodology and results of acute dry-land training intervention programs on swim start performance.

Reference	Participants Sex Age (years) Anthropometrics (mean ± SD)	Dry-land training intervention protocol	Start technique	Swim test	Swim start key performance measures (units)		Results		
					Kinematics	Kinetics			
Trunk activation exercises									
Iizuka et al. (79)	9 elite level swimmers (M) 20.2 ± 1.0 yrs 1.74 ± 0.04 m; 68.9 ± 4.1 kg	Three trunk stabilisation exercises	Kick start	1 x swim start to 5 m			Pre	Post	
					T5m (s)		0.83 ± 0.04	0.81 ± 0.04*	
					V5m (m/s)		4.61 ± 0.46	4.87 ± 0.35*	
Post-activation potentiation									
Cuenca-Fernandez et al. (82)[a]	14 recreational swimmers (10 M, 4 F) 17 to 23 yrs 1.76 ± 0.09 m; 69 ± 11.4 kg	LWU: 1 x 3 each leg @ 85 % 1RM YWU: 1 x 4 each leg @ MVC	Kick start	1 x maximal effort swim start to 15 m under competition rules			SWU	LWU	YWU
					T5m (s)		1.75 ± 0.05	1.71 ± 0.05*	1.65 ± 0.04*
					T15m (s)		7.54 ± 0.23	7.40 ± 0.21	7.36 ± 0.22*
Cuenca-Fernandez et al. (81)[b]	17 national level swimmers (M) 18.4 ± 1.4 yrs 1.81 ± 0.02 m; 73.7 ± 9.0 kg	RMWU: 1 x 3 each arm + 1 x 3 each leg @ 85 % 1RM EWU: 1 x 4 each arm + 1 x 4 each leg @ MVC	Unspecified	1 x maximal effort 50 m race under competition rules			SWU	RMWU	EWU
					T5m (s)		1.57 ± 0.11	1.52 ± 0.13*	1.52 ± 0.13*
					V5m (m/s)		3.12 ± 0.28	3.27 ± 0.29*	3.28 ± 0.27*
					V10m (m/s)		1.79 ± 0.17	1.83 ± 0.15*	1.84 ± 0.16*
Kilduff et al. (80)[a]	9 international level sprint swimmers (7 M, 2 F) 22 ± 2 yrs 1.79 ± 0.14 m; 77.9 ± 11.2 kg	Barbell back squat 1 x 3 @ 87 % 1RM	Unspecified	1 x swim start to 15 m under 50 m FS race conditions			Pre	Post	
						sPFv (N)	1462 ± 280	1518 ± 311*	
						sPFh (N)	770 ± 228	814 ± 263*	

1RM = one repetition maximum; EWU = arm stroke and split stance lunge on flywheel inertial device; F = females; FS = freestyle; LWU = split stance lunge on Smith machine; M = males; MVC = maximum voluntary contraction; RMWU = arm stroke and split stance lunge on Smith machine; SD = standard deviation; sPFh = starting peak horizontal forces; sPFv = starting peak vertical forces; SWU = standard warm-up; T5m = time to 5 metres; T15m = time to 15 metres; V5m = average velocity at 5m; V10m = average velocity from 5m to 10m; YWU = YoYo split stance lunge on flywheel inertial device; $p < 0.05$*

[a] 8 minutes’ rest in between post-activation potentiation stimulus and swim start; [b] 6 minutes’ rest in between post-activation potentiation stimulus and swim start

Table 3-6. Summary of participant background, methodology and results of chronic dry-land training intervention programs on swim start performance.

Reference	Participant Sex Age (years) Anthropometrics (mean ± SD)	Dry-land training Intervention protocol Intervention duration	Start technique	Swim test	Swim start key performance measures (units)		Results	
					Kinematics	Kinetics		
Plyometric exercises								
Bishop et al. (83)	22 adolescent swimmers (not stated) PT: 13.1 ± 1.4 yrs; control: 12.6 ± 1.9 yrs PT: 1.63 ± 0.12 m; control: 1.58 ± 0.12 m PT: 50.6 ± 12.3 kg; control: 43.3 ± 11.6 kg	2 x 60 minutes/ week consisting of skips, hops and jumps for lower body 8 weeks	Preferred technique	1 x swim start to 5.5 m			Pre	Post
					T5.5m (s)		Control: 3.94 ± 0.39 PT: 3.88 ± 0.48	Control: 3.82 ± 0.38 PT: 3.29 ± 0.47 PT vs control***
					TOV(m/s)		Control: 1.17 ± 0.10 PT: 1.29 ± 0.18	Control: 1.10 ± 0.16 PT: 1.48 ± 0.15 PT vs control***
Rebutini et al. (19)	10 national level swimmers (7 M, 3 F) M: 22 ± 1.4 yrs; F: 21.3 ± 7.6 yrs M: 1.78 ± 0.06 m; 69.8 ± 4.8 kg F: 1.70 ± 0.05 m; 59.9 ± 2.9 kg	2x/ week long jump training consisting of maximal horizontal and maximal long jumps 9 weeks	Preferred technique	Best of 2 x maximal effort swim starts to 15 m under competition rules			Pre	Post
						sPFh (N)	837 ± 153	847.33 ± 164.23*
						IMP (N/s)	221.9 ± 61.6	242.5 ± 60.9*
					TOV (m/s)		1.93 ± 0.18	2.13 ± 0.28*
					hTOV (m/s)		1.84 ± 0.19	2.14 ± 0.21*
Rejman et al. (56)	9 national level swimmers (M) 21.9 ± 3.4 yrs 1.79 ± 0.001 m; 75.1 ± 6.6 kg	2 x 60 minutes/ week consisting of skips, bounds, hops and jumps 6 weeks	Track start	Best of 3 x swim start to 5 m			Pre	Post
					T5m (s)		1.87	1.73***
					TOV (m/s)		1.88	2.14**
Resistance training								
Garcia-Ramos et al. (84)[a]	13 international level swimmers (5 M, 8 F) 18.1 ± 3.4 yrs 1.72 ± 0.08 m; 62.6 ± 8.5 kg	Variations of the squat, deadlift, hip thrust, leg flexion and extension exercises 3 weeks	Kick start	Best of 2 x swim starts to distance slightly further than 15 m			Pre	Post
					T10m (s)		4.37 ± 0.42	4.47 ± 0.39*
					T15m (s)		7.26 ± 0.51	7.54 ± 0.61*

F = females; hTOV = horizontal take-off velocity; IMP = impulse; M = males; PT = plyometric training; sPFh = starting peak horizontal forces; T5m = time to 5 metres; T5.5m = time to 5.5 metres; T10m = time to 10 metres; T15m = time to 15 metres; TOV = take-off velocity; $p < 0.05$*; $p < 0.01$**; $p < 0.001$***

[a] Only sea level data were included

3.6 DISCUSSION

The main findings from the cross sectional studies included in this review are that swim start performance, as assessed by the time taken to reach predetermined set distances of 5, 10 and 15 m, was more highly related to (1) vertical SJ and CMJ than measures of maximal muscle strength, (2) body weight than loaded vertical jumps and (3) jump height than other jump kinetic or kinematic measures. The primary findings from the intervention studies included in this review were: (1) post-activation potentiation is an effective training strategy to acutely improve swim start performance, (2) plyometrics can significantly improve swim start performance in as little as six weeks.

3.6.1 RELATIONSHIP BETWEEN DRY-LAND EXERCISES AND SWIM START PERFORMANCE

A number of outputs from a variety of lower body exercises have been examined within the literature to determine their relationships to swim start performance. As the outputs of many of these lower body exercises exhibited nearly perfect ($r \geq 0.9$), very large ($r = 0.7 – 0.9$) or large ($r = 0.5 – 0.7$) correlations with swim start performance across a variety of levels of swimmer, the results of this systematic review confirmed the importance of lower body power and strength for optimising swim start performance. The strongest relationships with swim start performance were observed for bodyweight vertical jumping exercises (CMJ and SJ), which demonstrated nearly perfect correlations (73, 74). Large to very large correlations were observed between the time required to complete distances of between 5 – 15 m and performance in loaded SJ at four different loads (72, 77). Traditional strength exercises and measures of maximal muscle strength of the lower body also had a very large correlation with time to 15 m. These results suggest that a range of outputs from a variety of lower body dry-land resistance training exercises can be used to determine the lower body strength and power capacities of swimmers required for the swim start. This may reflect the requirement for high levels of force and power to be developed across the ankle, knee and hip joints and for these to be coordinated effectively with those of the upper body to maximise take-off velocity.

The different swim start techniques used in the studies identified in this systematic review may have some implications in the comparison of the results between studies. For example, even though both Benjanuvatra et al. (73) and Garcia-Ramos et al. (72) included bodyweight CMJ and SJ in their studies, there is a discrepancy between the results obtained in both studies. Benjanuvatra et al. (73) reported a nearly perfect relationship between the take-off velocity of both bodyweight CMJ and SJ with time to 5 m, whereas Garcia-Ramos et al. (72) reported a moderate to large relationship between the take-off velocity in the bodyweight CMJ with time to 10 m and 5 m, and a large relationship between the take-off velocity of the bodyweight SJ and time to 5 m. These discrepancies may be explained by the swim start technique used in each study. Benjanuvatra et al. (73) utilised the grab start, while Garcia-Ramos et al. (72) utilised the track start, with the difference between these two start techniques being the foot placement on the blocks. Pupišová & Pupiš (76) who assessed swim start performance in both grab and track start conditions, reported a small correlation in the flight phase of the track start and a very large correlation in the flight phase of the grab start with the vertical jump. Unfortunately, no clear details were provided on whether this was a concentric only squat jump or a countermovement jump (76). Furthermore, this study also had a very small sample size of seven swimmers and other important aspects of the methodology were somewhat unclear or did not reflect what is typically performed in the swim start. Notably, Pupišová & Pupiš (76) stated in their methodology that the swim start was performed without any underwater kicks and had swimmers glide to 7 m and 9 m. This does not represent the typical action of a swimmer of the underwater phase in the swim start, where undulatory kicks are used to maintain as much entry velocity as possible (34).

3.6.2 ACUTE CHANGES IN SWIM START PERFORMANCE AFTER DRY-LAND RESISTANCE TRAINING INTERVENTION

PAP can be described as a training method to improve muscle contractility, strength and speed in sporting performance by performing a small number of repetitions at maximal or near maximal effort, also referred to as conditioning activity (CA) (85), several minutes before an explosive activity (86, 87). The use of PAP in the field of strength and conditioning has grown rapidly, with performance enhancement effects of PAP demonstrated in athletic movements such as jumping and sprinting (86). The CA is able to potentiate the neuromuscular system, thereby allowing acute improvements in performance to be observed several minutes later as the acute fatigue from the CA diminishes (88). Several mechanisms have been suggested for the acute PAP phenomenon, including greater recruitment of higher order motor units, increase in pennation angle and the phosphorylation of myosin regulatory light chains (89).

Four studies were identified that have examined the potential acute benefits of resistance training prior to swimming start performance, with three of these studies utilising a PAP approach (80-82). Cuenca-Fernández et al. (82) demonstrated a positive PAP effect with respect to the time required to cover a distance of 5 m and 15 m. It was also observed that a greater reduction in these times to 5 m and 15 m was observed after the use of the split stance lunge on the flywheel inertial device at maximal voluntary contraction than the split stance lunge at 85 % 1RM on the Smith machine. These results are consistent with the later study by Cuenca-Fernández et al. (81), who included the arm strokes, with one PAP protocol consisting of one set of three lunge and three arm stroke repetitions on the Smith machine at 85 % of 1RM , while the other protocol comprised one set of four repetitions of both the upper and lower limb on a flywheel inertial device at maximum voluntary contraction. Both PAP protocols (81) demonstrated a shorter time to 5 m in comparison to a standard warm-up, however, there was no difference in the time to 5 m between those two interventions. Conversely, Kilduff and colleagues (80), who assessed the acute effects of one set of three repetitions of heavy, 87 % of 1RM back squat on start performance, did not observe any significant reduction in the only time they recorded, i.e. the time to 15 m, but reported significant improvements in peak horizontal and peak vertical forces post PAP intervention.

Within the PAP literature, the kinematic and kinetic similarity between the CA and the subsequent movement has been reported to be an important factor, with studies in the sprint literature indicating greater PAP effects when movement patterns of the CA are followed by a biomechanically similar explosive activity (90, 91). Thus, the utilisation of a split stance rather than traditional squat may further increase this PAP effect due to the PAP protocols being more biomechanically similar to the foot position and direction/timing of force application in the kick start technique on the OSB11 start block. The significant improvements in time to 5 m (81, 82) and 15 m (82) and peak horizontal and peak vertical forces (80) observed post PAP intervention suggest some benefits of using PAP as a pre-race warm-up to enhance a swimmer's swim start performance. However, the duration over which the potentiation effect lasts may be too short to be utilised as a component of pre-competition warm-ups in swimming competitions. A meta-analysis by Gouvêa et al. (85) of PAP on jumping performance has shown that an optimal PAP effect was found with a recovery period of 8 to 12 min after the preceding CA, with the PAP effect dissipating after a recovery period of 16 min or more. Specifically, Cuenca-Fernández et al. (81) utilised a rest period of 6 min and Cuenca-Fernández et al. (82) and Kilduff et al. (80) utilised a rest period of 8 min between the CA and the explosive activity i.e. swim start. During competitions, swimmers may have to wait in marshalling areas for a period of up to 20 min after they complete their warm-up until they compete in their specific events. This could pose some current challenges as to how a PAP stimulus may be used to enhance swim start performance as a pre-competition warm-up strategy, especially as the successful PAP interventions identified in the current review have utilised heavy resistance training devices that would not be available in the marshalling areas.

In addition to using PAP to achieve short term performance enhancement, it has been suggested that PAP can be manipulated to enhance the training stimulus of explosive strength exercises to induce greater chronic training-related adaptations than traditional resistance training exercises. The manipulation of PAP within a resistance training program is also known as complex training (92). Complex training combines heavier resistance training exercise with a lighter load power-oriented exercise in an attempt to transfer gains in strength to power (92). The rationale for this complex pairing of exercises was that the heavy resistance strength-oriented set would provide an enhanced neural drive, which would then carry over to the lifting of the lighter resistance explosive exercise, resulting in a greater power output in the explosive exercise than would occur without the prior heavy resistance set (93). PAP may be a viable training method when incorporated into a swimmer's regular dry-land resistance training program and possibly contribute to enhanced swim start performance after several months of training. However, due to the lack of any such chronic PAP studies involving swimmers, future studies are required to document whether significant chronic adaptations in physical capacities and swim start performance can be observed after a PAP training program.

Trunk stability is an important component in swimming as it allows for an efficient transfer of forces between the trunk and the upper and lower extremities to propel the body through the water and off the start blocks (94). Weston et al. (95) have demonstrated chronic improvements in swimmers' core function and 50 m front crawl swim time with the implementation of a 12-week isolated trunk training program. Within the scope of this review, Iizuka et al. (79) demonstrated significant acute improvements in swim start performance as a result of acute resistance training exercises for the trunk. The authors suggested that the trunk stabilisation exercises provided enhanced trunk stability which led to an immediate improvement in time to 5 m and average velocity over 5 m.

3.6.3 CHANGES IN SWIM START PERFORMANCE AFTER DRY-LAND RESISTANCE TRAINING INTERVENTION

The combined use of dry-land resistance training and swim training is a common practice in competitive swimming (42, 44). By overloading the muscles required for swimming with external resistances, a dry-land resistance training program aims to increase the strength and power production of muscles that play important roles in competitive swimming events (96, 97). Dry-land resistance training modalities can include ballistic training such as Olympic style lifts e.g. cleans and their variations as well as plyometric activities, while non-ballistic training includes the use of free weight, bodyweight and/or machine based exercises (1, 42). Plyometric training refers to the performance of stretch-shortening cycle (SSC) movements involving a short duration, high velocity eccentric contraction followed by a rapid concentric contraction (98). Athletes who can effectively use the SSC can produce significantly greater concentric force, velocity and power compared to what is possible in concentric only muscular contractions. The mechanisms contributing to this effect reflects specific neural adaptations of the SSC, the storage and utilisation of elastic strain energy, the stretch reflex and/or an increase in the active state of the muscle (99, 100). Engaging in a plyometric training program that requires fast muscular contraction of the lower body has been demonstrated to significantly improve swim start performance in all three studies identified in this systematic review (19, 56, 83), with significant improvements in key swim start parameters, such as time to 5 m and 5.5 m, take-off velocity and horizontal forces and impulse observed. As the swim start is a predominantly concentric movement, these specific training adaptations from the plyometric training studies would appear to be a direct result of the swimmers' ability to activate the muscles during the eccentric and isometric phases of the SSC , which then allows for the muscle to be in a higher active muscle state and provide additional propulsive forces during the concentric phase of the SSC (98, 101, 102).

In the study conducted by Rebutini et al. (19), the authors hypothesised that the long jumps performed in the training program would be effective in improving the kinetics of the swim starts because they required the production of horizontal forces at similar velocities to the actual swim start. Such a hypothesis was consistent with the results of these studies, with significant increases in swim start horizontal take-off velocity, peak horizontal forces and/or horizontal impulse observed by Rebutini et al. (19), and time to 5 m and take-off velocity by Rejman et al. (56).

The available evidence on dry-land resistance training with free weights is limited. In this systematic review, we only found one study (84) that included resistance training exercises such as variations of the squat, deadlift, hip thrust, leg flexion and extension exercises, although such exercises appear to be commonly used by competitive swimmers. Results indicated no significant difference in swim start performance after the three-week dry-land resistance training program that was performed prior to the altitude training camp. When comparing results of this study involving resistance training exercises (84) to the three studies involving plyometric training (19, 83, 87), it was apparent that the three weeks of traditional resistance training was of substantially shorter duration than six to nine weeks of plyometric training (19, 56, 83). Furthermore, the swimmers were performing two swim sessions and one dry-land (some combination of resistance, cardiovascular and flexibility) session six days per week (84). This three-week resistance training program involved a substantially greater weekly training load than the three plyometric studies. Due to these differences between the one traditional resistance training and three plyometric studies, it is difficult to determine on the basis of the current evidence whether plyometric, traditional resistance training or a combined approach may be most useful for improving swim start performance. Beyond the differences in training duration and weekly loads, it is also possible that the specificity principle may also underlie the potentially greater adaptations currently found for plyometric than traditional resistance training for improving swim start performance. Specifically, the more specific a training exercise is to a competitive movement, including the velocity, direction and time of force application, the greater the likely transfer of the training effect to performance (55, 103). The studies by Rebutini et al. (19) and Rejman et al. (56) shared a key feature in their plyometric training programs, which is an emphasis on the horizontal direction in the plyometric exercises performed. Rebutini et al. (19) included long jumps in their plyometric training intervention and Rejman et al. (56) modified the starting position of the plyometric exercises to better simulate the swimming start and to emphasise a greater horizontal direction of take-off. The improvements in swim start performance observed with all three plyometric studies (19, 56, 83) appear to be indicative of the potential for different forms of plyometric training to elicit significant improvements in swimming start performance with as little as six to nine weeks of training.

3.7 METHODOLOGICAL CONSIDERATIONS

3.7.1 MEASUREMENT OF THE SWIM START

Of the eight cross-sectional and eight intervention studies included in this systematic review, only four studies (77, 79, 82, 84) utilised the kick start technique and the OSB11 start block that is currently used in competitive swimming. Even though the track start utilised in four (56, 72, 75, 76) out of the 16 studies included in this systematic review may have some similarities to the kick start technique currently used in competitive swimming, Honda et al. (30) have identified that the additional kick plate on the OSB11 start block is capable of significantly improving both time to 5 m and 7.5 m, with a further 0.04 s improvement obtained in the kick start compared to the track start technique at both distances. This is attributed to an increase in horizontal force production that is able to be produced by the rear leg on the kick plate of the OSB11 starting block, which ultimately increases horizontal take-off velocity (30).

The eight cross-sectional studies included in the review exhibited some degree of inconsistency with the measurement of the swim start performance kinematic measures, such as the time to set distances of 5, 10 and/ or 15 m. The majority of the studies (10, 72, 73, 77) measured swim start time when the head crossed the specified distances in their study. Two studies (75, 78) measured swim start time when the fingertips crossed 10 m, with the two other studies (74, 76) not specifying how the start time to 15 m was measured. For the intervention studies, four intervention studies (19, 81, 82, 84) measured the time to set distances when the head crossed the specified distance, while Iizuka et al. (79) measured the time to 5 m when the fingertips crossing 5 m. Despite reporting the same measure of the time to distances of 5 m and 5.5 m, there appears to be a discrepancy in the values reported between the training intervention study by Rejman et al. (56) and Bishop et al. (83). This is due to the difference in how the swim start was quantified in both studies. Rejman et al. (56) quantified time to 5 m from the time from the final shift of centre of mass from the edge of the starting block to a distance of 5 m, whereas Bishop et al. (83) recorded time to 5.5 m using the time from starting stimulus to the point in time at which the head made contact with the water surface.

There also appear to be some differences in the nature of the swim task performed across these studies. Within this review, the majority of the studies tested the swimmers under competition rules (10, 19, 72-75, 78, 80-83). In contrast, some studies included a dive and glide test (56, 76) while Garcia-Ramos (77) had swimmers perform undulatory kicks till 15 m. Therefore, it is possible that variety of swim start methodologies used may have significant implication in the comparison of results between studies.

3.7.2 STRENGTH DIAGNOSTICS

Tests of muscular strength and/or power qualities are commonly performed to assess training-induced changes and the efficacy of a strength and conditioning program in many athletic populations (104). For sports requiring high to very high levels of muscular strength, maximal and submaximal strength assessments or isometric assessments such as the isometric mid-thigh pull are commonly used (104). For dynamic performance qualities, vertical lower body jumping exercises are common measurement tools of athletic lower body force and power ability (105).

The majority of the cross-sectional (10, 72-74, 76-78) and one intervention study (84) identified in this systematic review utilised dynamic lower body exercises such as the CMJ and SJ as a measurement of lower body power. Only two of eight cross-sectional studies (10, 74) and four of eight intervention studies (19, 80-82) included any maximal strength assessments. The relative lack of maximal strength assessments compared to explosive total body jumping exercises in this systematic review may reflect the task demands of the swim start whereby high levels of lower body power rather than maximal muscle strength are required to enhance swim start performance.

3.7.3 STUDY POPULATION

The magnitude of difference in strength characteristics and response to a resistance training program can be affected by sex, age and training status (106). Majority of the studies reviewed generally consisted of a small sample size and a potentially greater bias towards male compared to female participants. Only two of the cross-sectional studies had all female swimmers and the four studies that had a mix of females and males had an uneven split of both sexes, with a greater number of male participants compared to females. In addition, the majority of studies did not provide any clear description of the resistance training experience or the baseline levels of lower body muscular strength of their participants. Specifically, only two (10, 74) out of the eight cross-sectional and three acute intervention studies (80-82) included any details regarding the baseline strength level of the swimmers. As such, it is difficult to determine how sex, age and training status may influence the relationship and/or training response between dry-land jump performance to swim start performance.

3.7.4 STUDY DESIGN

With respect to the intervention studies, one factor for potential bias could be the research design and statistical analyses used in the studies. Only one (83) out of the eight intervention studies identified utilised a controlled trial design with an intervention and control group, with the remainder of the studies using a within group pre-post test statistical comparison using ANOVA or paired t-tests.

The lack of control groups and the use of a within group statistical analysis approach in the intervention studies make it difficult to determine whether the improvements in swim start performance were a result of the dry-land resistance training intervention, or whether they were related to the overall swim training program. One possible reason for the lack of randomised controlled trials may reflect the relatively limited sample size of high performance swimming squads.

3.8 CONCLUSION

Within the limits of the review, the current literature indicates that a range of lower body strength and power measures are highly correlated with swim start performance, with these correlations appear greatest when utilising body weight vertical jumping exercises. These findings would suggest that assessing vertical jump performance would be a better diagnostic tool to assess lower body power capabilities than traditional strength assessments for swim start performance. Significant acute and chronic swim start performance benefits can be obtained using a PAP training protocol and lower body plyometric exercises that are primarily horizontal in direction, respectively. Despite the relative homogeneity of participants in the studies included in this review, the results across intervention studies suggest that significant improvements in swim start performance can be obtained from both a PAP training protocol and plyometric exercises independent of skill level.

Due to the relative lack of research with the currently used OSB11 starting block and kick start technique, future cross-sectional and intervention studies should utilise the current start block and start technique to confirm that the findings highlighted in this review applies to current practices in competitive swimming. Given that swimmers simultaneously integrate swim training and dry-land resistance training within a periodised program to develop muscular strength and power capabilities (1, 42), additional research should also compare the potential benefits of different dry-land resistance training approaches to provide a better understanding of the development of strength and conditioning programs more conducive to improving swim start performance.

CHAPTER 4: THE PREDICTION OF SWIM START PERFORMANCE BASED ON SQUAT JUMP FORCE-TIME CHARACTERISTICS

4.1 PREFACE

The literature reviewed in Chapter 3 highlighted that performance in a range of lower body strength and power exercises is highly correlated to swim start performance, with these correlations appearing greatest when utilising bodyweight vertical jumps (countermovement jump and squat jump (SJ)). However, several gaps exist in the current literature regarding what the most important lower body force-time characteristics required for swim start performance as assessed by times to 5 m and 15 m are. Issues such as small sample sizes (*n* = 7 – 27), greater proportion of male participants as compared to females, and the lack of research using the OSB11 start block and the kick start technique currently used in competitive swimming meant that the findings of the systematic review (Chapter 3) might not necessarily apply to high performance swimmers competing today. Therefore, this chapter aimed to utilise a larger sample of high performance male and female swimmers compared to previous studies to determine the key lower body force-time characteristics using the SJ to predict swim start times to 5 m and 15 m.

This chapter is the first experimental chapter of this thesis, with the findings obtained in this study informing the lower body force-time variables used for analysis in Chapters 6 and 7.

This manuscript was published in PeerJ, with a copy of the manuscript found in Appendix 7. A copy of the supplementary material of this chapter is included in Appendix 8.

Citation:

Thng S., Pearson S., Rathbone E., Keogh J.W.L. The prediction of swim start performance based on squat jump force-time characteristics. PeerJ. 2020 Jun 1;8:e9208. This is an Open Access article reproduced under a Creative Commons Attribution 4.0 International License CC BY 4.0.

4.2 ABSTRACT

Depending on the stroke and distances of the events, swim starts have been estimated to account for 0.8 % to 26.1 % of the overall race time, with the latter representing the percentage in a 50 m sprint front crawl event (12). However, it is still somewhat unclear what are the key physiological characteristics underpinning swim start performance. The primary aim of this study was to develop a multiple regression model to determine key lower body force-time predictors using the squat jump for swim start performance as assessed by time to 5 m and 15 m in national and international level swimmers. A secondary aim was to determine if any differences exist between males and females in jump performance predictors for swim start performance. A total of 38 males (age 21 ± 3.1 years, height 1.83 ± 0.08 m, body mass 76.7 ± 10.2 kg) and 34 females (age 20.1 ± 3.2 years, height 1.73 ± 0.06 m, body mass 64.8 ± 8.4 kg) who had competed at either an elite (*n* = 31) or national level (*n* = 41) participated in this study. All tests were performed on the same day, with participants performing three bodyweight squat jumps on a force platform, followed by three swim starts using their main swimming stroke. Swim start performance was quantified via the time to 5 m and 15 m using an instrumented starting block. Stepwise multiple linear regression with quadratic fitting identified concentric impulse and concentric impulse^2 as statistically significant predictors for time to 5 m (R^2 = 0.659) in males. With time to 15 m, concentric impulse, age and concentric impulse^2 were statistically significant predictors for males (R^2 = 0.807). A minimum concentric impulse of 200 – 230 N.s appears required for faster times to 5 m and 15 m, with any additional impulse production not being associated with a reduction in swim start times for most male swimmers. Concentric impulse, Reactive strength index modified and concentric mean power were identified as statistically significant predictors for female swimmers to time to 5 m (R^2 = 0.689). Variables that were statistically significant predictors of time to 15 m in females were concentric impulse, body mass, concentric rate of power development and Reactive strength index modified (R^2 = 0.841). The results of this study highlight the importance of lower body power and strength for swim start performance, although being able to produce greater than 200 or 230 N.s concentric impulse in squat jump did not necessarily increase swim start performance over 5 m and 15 m, respectively. Swimmers who can already generate greater levels of concentric impulse may benefit more from improving their rate of force development and/or technical aspects of the swim start performance. The sex-related differences in key force-time predictors suggest that male and female swimmers may require individualised strength and conditioning programs and regular monitoring of performance.

Keywords: swimming, strength and conditioning, resistance training, swim start, dry-land

4.3 INTRODUCTION

Swim start performance has been identified as a determining factor for success, especially in sprint distance events, as it is the part of the race that the swimmer is travelling at the fastest velocity (12, 14). While the exact nature of starts may differ between the four swimming strokes, there are three primary phases that contribute towards the overall start performance. The block phase requires a quick reaction to the starting signal and a large take-off velocity that is primarily horizontal in direction (107). The subsequent flight phase is an example of projectile motion, whereby the swimmer becomes airborne and finishes when they contact the water (14, 20). The flight phase is followed by the underwater phase, in which swimmers attempt to maintain a streamlined position with their arms outstretched in front of the head to minimise velocity loss while also performing multiple propulsive undulatory leg kicks (except in breaststroke) until their head resurfaces before the 15 m mark (8). The block, flight, and underwater phase account for approximately 11 %, 5 %, and 84 % respectively of the total start time (20). The average velocity during the underwater phase is highly dependent on the take-off velocity acquired in the block phase, the horizontal distance obtained in the flight phase, as well as the degree of streamlining and effectiveness of the undulatory leg kicks during the underwater phase (14).

As close margins often exist between medallists in sprint swimming events, being able to identify areas to achieve marginal gains in performance by tenths or even hundredths of a second can make a difference in overall performance (83). Previous research has highlighted a key component of swim start performance is the ability to produce high forces off the starting block. In a recent systematic review of eight cross-sectional studies, Thng et al. (108) observed significant correlations between vertical jump and lower body strength scores to swim start performance in swimmers of a variety of standards, with these correlations typically higher for the jump than strength tests. Specifically, near perfect correlations ($r > 0.90$) between jump height or take-off velocity and swim start performance were observed in the eight studies. This might be due to the set-up of the SJ, which might be biomechanically similar to the set-up in the block phase of the swim start, due to the concentric nature of the SJ. The results of this systematic review highlight the importance of lower body power and strength as an important component of swim start performance. However, out of the 8 cross-sectional studies identified in the systematic review (108), only one study utilised the OSB11 start block (OMEGA, Zurich, Switzerland) that is currently used in competitive swimming (77). The OSB11 start block which was introduced by FINA in 2010 has an angled kick plate at the rear of the block that allows the swimmer to adopt a kick start technique. Honda et al. (30) have identified that the angled kick plate on the OSB11 start block is capable of significantly improving both time to 5 m and 7.5 m, with a further 0.04 s improvement obtained in the kick start compared to the track start technique performed on the previous starting block. This is attributed to an increase in horizontal force application and subsequent take-off velocity from the additional contribution of the rear leg on the kick plate. This view of Honda et al. (30) was consistent with the findings of Slawson et al. (20) who observed higher peak horizontal and vertical force generation with the OSB11 start blocks in elite swimmers, with these forces significantly correlated to a better start performance as assessed by block time, take-off velocity and flight distance.

In addition, all of the studies described in the systematic review by Thng et al. (108) only involved correlational analyses. While correlations describe the nature of a relationship between two variables, other statistical approaches such as multiple linear regression may provide more information regarding what power and strength variables (hereafter referred to as force-time characteristics) of jumping performance that best predict swim start performance in high performance swimmers. The lack of research using the OSB11 start block and kick start technique in these correlation studies needs to be addressed, as this relative lack of ecological validity with the start technique used in seven of the eight published studies may limit the generalisability to contemporary high-performance swimming.

Another limitation of the previous literature is the small sample sizes of recreational to sub-elite swimmers (*n* = 7 – 27) and the relative focus on male swimmers at the expense of their female counterparts. This is a concern as previous research has established differences in force and power capabilities between males and females in other athletic activities (109, 110). For example, a number of studies has observed that males are able to produce higher velocities at the same percent of one repetition maximum and have a greater rate of force development and countermovement jump height than females (109-112). Rice et al. (109) concluded that this greater jump height observed in males compared to females can be attributed to larger concentric impulse and thus greater velocity throughout most of the concentric phase at take-off in the countermovement jump. Further, the higher rate of force development and ability to produce greater velocities at the same percentage of one repetition maximum in males may be a result of greater muscle thickness and cross-sectional area, greater percentage of fast-twitch muscle fibres, greater concentration of anabolic hormones and higher neural activity during muscle contractions compared to females (113). From a practical standpoint, these sex-related differences in force-time characteristics suggest there might need to be some potential differences in aspects of athletic monitoring and strength and conditioning programs between high-performance male and female swimmers.

The primary objective of this study was to develop a multiple regression model to determine key lower body force-time predictors for swim start performance using the squat jump in high performance swimmers. Considering the potential sex differences in force-time characteristics during jumping, a secondary aim was to determine if differences exists between males and females in jump performance predictors for swim start performance.

4.4 MATERIALS AND METHODS

4.4.1 STUDY DESIGN

A cross-sectional study design was used to quantify the relationship between squat jump (SJ) force-time variables to swim start performance as assessed by times to 5 m and 15 m in national and international level swimmers. All tests were performed on the same day, with participants first performing SJ testing on the force platform, followed by a swim start performance test with a 30-minute recovery period in between each testing session.

4.4.2 PARTICIPANTS

Thirty-eight males and 34 females who had competed at either an elite (*n* = 31) or national level (*n* = 41) in front crawl, butterfly or breaststroke participated in this study. Backstroke was excluded due to the start being initiated from within the water, instead of on the elevated OSB11 starting block. Elite level swimmers comprised of swimmers who had competed internationally in either the Olympics, Commonwealth Games or World Championships. National level swimmers comprised of swimmers that have at least 2 years of experience in competing at a national level and competed at the most recent national championships. Swimmers were required to have at least 1 year of land-based resistance training experience under the supervision of a strength and conditioning coach.

All participants gave written informed consent to participate in the study, which was conducted in accordance with the Declaration of Helsinki and approved by Bond University Human Research Ethics Committee (0000016006), The University of Queensland Human Research Ethics Committee (HMS17/41) and Swimming Australia Ltd.

4.4.3 SQUAT JUMP TEST

Prior to the SJ test, participants completed a dynamic lower body warm-up under the supervision of a strength and conditioning coach. Following the warm-up, participants were given two practice jumps before the test was conducted. Jumps were performed on a force platform (ForceDecks FD4000, London, United Kingdom), with a sample rate of 1000 Hz. Participants started in an upright standing position with their hands on their hips. They were then instructed to adopt a squat position using a self-selected depth that was held for 3 seconds before they attempted to jump as high as possible (57). A self-selected squat depth was chosen as it has been reported to produce the greatest jump height and higher peak force outputs in comparison to measured squat depths (58). A successful trial was one that did not display any small amplitude countermovement at the start of the jump phase on the force trace (59). All participants were asked to perform three maximal intensity SJ with a 30-second passive rest in between each effort.

The SJ trial with the highest jump height was kept for data analysis. Jump height was determined by the conventional impulse-momentum method (Jump Height = $v^2/2g$, where v = velocity at take-off and g = gravitational acceleration) (114). Ground reaction force data from the SJs were analysed using the commercially available ForceDecks software (ForceDecks, London, United Kingdom). Out of the variables provided by ForceDecks, 46 variables, excluding any left to right asymmetry variables were initially extracted for use in further analysis. Descriptions of the SJ variables are provided in Appendix 8.

4.4.4 SWIM START PERFORMANCE TEST

After completing a self-selected warm-up based on their usual pre-race warm-up routine, participants then performed three maximal effort swim starts with their main swim stroke (front crawl (n = 50), butterfly (n = 12), or breaststroke (n = 10)) while wearing their regular swim training swimsuits. Trials were started as per competition conditions and swimmers were instructed to swim to a distance past the 15 m mark, in order to ensure that representative values at the 15 m distance were obtained (115). Two-minutes of passive recovery was given between each trial (60). The start with the fastest time to 5 m for each individual with all swim strokes were selected for further analysis.

All 72 participants were included in the time to 5 m analysis irrespective of stroke performed, as the technical execution of the swim start does not differ until after 5 m. To avoid the potential confounding influence of the speed differences in both the underwater and swim phases of butterfly and breaststroke, only front crawl was included for time to 15 m analysis as it comprised of majority of the sample ($n = 50$).

Swim start performance were collected using a Kistler Performance Analysis System – Swimming (KPAS-S, Kistler Winterthur, Switzerland), which utilises a force instrumented starting block, constructed to match the dimensions of the Omega OSB11 block (KPAS-S Type 9691A1; Kistler Winterthur, Switzerland). Time to 5 m and 15 m were collected using five calibrated high speed digital cameras collecting at 100 frames per second, synchronised to the instrumented starting block using the KPAS-S. One camera was positioned 0.95 m above the water and 2.5 m perpendicular to the direction of travel to capture the start and entry of swimmer into the water, while the other three cameras were positioned 1.3 m underwater at 5 m, 10 m and 15 m perpendicular to the swimmer to capture the time to 15 m (Figure 4-1) (60). The times to 5 m and 15 m were defined as the time elapsed from the starting signal until the apex of the swimmers' head passed the respective distances (60). An Infinity Start System (Colorado Time Systems, Loveland, Colorado, USA) provided an audible starting signal to the athletes as well as an electronic start trigger to the KPAS-S system.

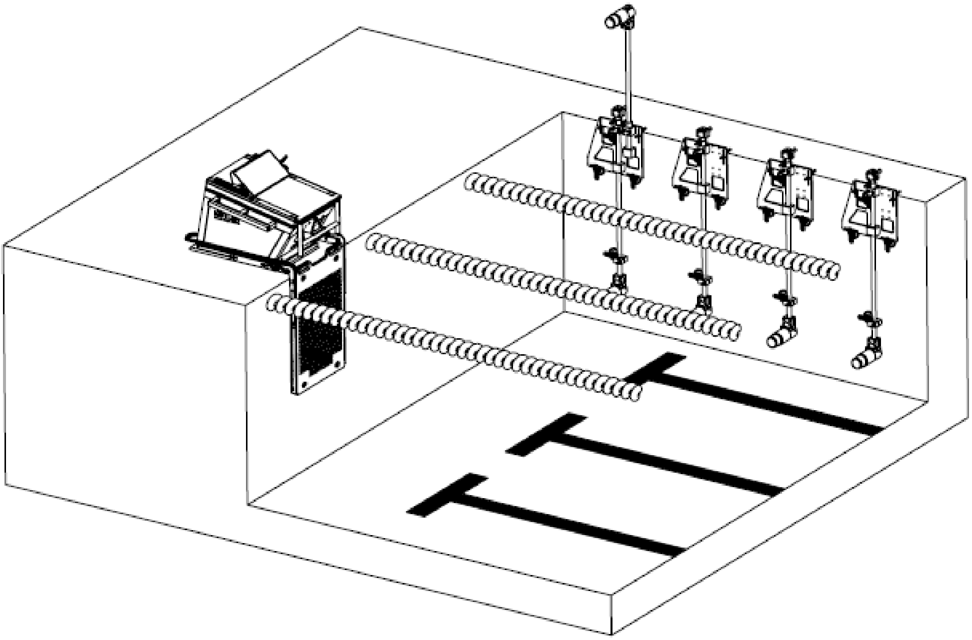

Figure 4-1. Overview of the camera set-up and the KiSwim instrumented starting block (Kistler Group, 2019) Reproduced with permission from Kistler Instrumente AG, Winterthur, Switzerland.

4.4.5 STATISTICAL ANALYSIS

Descriptive statistics are reported as mean ± SD for normally distributed continuous variables and frequency (%) for categorical variables. Normality was checked using histograms, normal Q-Q plots and the Shapiro-Wilk test. A principal component analysis (PCA) was used to identify optimal sets of key performance indicators on the 46 jump variables extracted from ForceDecks force platform (ForceDecks, London, United Kingdom). This method has been used in previous studies that sought to identify kinematic and kinetic predictors of athletic performance from a number of highly interrelated vertical jump performance measures (116, 117). A second PCA was conducted to explore the reduced dataset of 32 jump performance variables and identify the principal components (PC) summarising the primary force-time variables. The decision on a suitable number of PCs to retain in each PCA required eigenvalues of 1.0 or greater (Kaiser criterion) and was supported using a scree plot.

Multiple linear regression models using a stepwise regression method were initially performed to identify the potential predictors of the outcome variables of time (s) to 5 m and 15 m. Analyses were carried out on the entire dataset, and also on the data split by sex. Second order polynomial models were also investigated, as visual inspection identified that these quadratic models better matched the data for males than the linear models, with this also confirmed by significantly higher R^2 for the quadratic models (118, 119). Collinearity diagnostics were used to avoid the problem of multicollinearity. The assumptions of normality, linearity and homoscedasticity of residuals were verified. Results of the regression modelling are presented in terms of unstandardized coefficients, the 95 % CI and p-values, along with the R^2 and standard error of estimate. Data were analysed with statistical software R version 3.5.3 and SPSS version 23.0.0 (SPSS Inc., Chicago, IL). *P*-values less than 0.05 were deemed to indicate statistical significance.

4.5 RESULTS

Seventy-two swimmers, comprising 38 males and 34 females were included in this study. The physical characteristics of the participants are described in Table 4-1. Out of the 72 participants, 50 participants performed the swim start using the front crawl technique, with an additional 12 participants performing butterfly and 10 participants using breaststroke. Statistically significant differences among males and females were observed in a number of variables (Table 4-1), with males significantly heavier, taller and faster to 5 m and 15 m than females.

Table 4-1. Physical characteristics of participants (*N* = 72).

Variables	**Males**		**Females**	
	5 m (*n* = 38)	15 m (*n* = 26)	5 m (*n* = 34)	15 m (*n* = 24)
Age (years)	21.0 ± 3.1	21.2 ± 3.2*	20.1 ± 3.2	19.2 ± 3.2
Body mass (kg)	76.7 ± 10.2**	76.5 ± 11.0**	64.8 ± 8.4	64.2 ± 8.4
Height (m)	1.83 ± 0.08**	1.85 ± 0.08**	1.73 ± 0.06	1.73 ± 0.06
Time to 5 m (s)	1.48 ± 0.09**		1.65 ± 0.08	
Time to 15 m (s)		6.4 ± 0.44**		7.3 ± 0.5

All data is presented as means and standard deviations. *$p< 0.05$; **$p< 0.001$ between males and females.

In the first PCA analysis on the 46 jump variables extracted from ForceDecks force platform (ForceDecks, London, United Kingdom), four PCs which explained 82 % of the variance were identified. Thirty-two most influential jump variables were identified from this initial PCA. A secondary PCA was run to explore the new dataset of 32 jump performance variables. The first three components, which explained 93 % of the variance, were retained. From this set, 15 variables were identified as potential predictors in subsequent regression models (Table 4-2). The results revealed that Component 1 accounting for 67.5 % of the variance, was of predominantly kinetic component. Component 2 accounting for 17.1 % of the variation, was predominantly a time-dependent kinematic component. Lastly, Component 3 accounted for 8.5 % of the variation, with the highest load attributed to bodyweight.

Table 4-2. List of 15 most influential potential predictors of swim start performance identified from the PCA and their correlations with the principal components.

Potential predictors	**Principal Component**		
	PC1	**PC2**	**PC3**
Variation explained for each component	**67.5 %**	**17.1 %**	**8.5 %**
Bodyweight (BW)	-0.71	0.11	0.68
Concentric impulse	-0.88	0.31	0.34
Concentric mean force	-0.91	-0.09	0.39
Concentric mean power	-0.94	0.13	0.14
Concentric peak force	-0.92	-0.15	0.32
Concentric rate of power development (RPD)	-0.93	-0.31	0.04
Force at peak power	-0.92	-0.05	0.33
Peak power	-0.95	0.24	0.14
Reactive strength index modified (RSImod)	-0.90	-0.12	-0.20
Take-off peak force	-0.92	-0.15	0.32
Concentric peak velocity	-0.77	0.55	-0.29
Concentric rate of force development (RFD) BW	-0.59	-0.75	-0.15
Concentric RFD	-0.72	-0.66	0.05
Jump height (impulse-momentum)	-0.75	0.56	-0.31
Velocity at peak power	-0.68	0.66	-0.27

Linear stepwise multiple regression analyses were performed using the ForceDecks SJ data to predict time to 5 m (see Figure 4-2 and Table 4-3) and time to 15 m (see Figure 4-3 and Table 4-4) in the overall sample of males and females as well as male and female subgroups.

4.5.1 TIME TO 5 M

The scatterplot in Figure 4-2 shows a quadratic relationship between SJ concentric impulse and time to 5 m in males ($R^2 = 0.693$). For a fast time to 5 m for males, visual inspection of the data suggests a minimum concentric impulse production of around 180 – 200 N.s is required. While visual inspection of the model suggested no additional reduction in time to 5 m with a higher concentric impulse for most swimmers, there are some outlier individuals who appear to derive additional performance benefit from an increased concentric impulse up to approximately 230 N.s. The relationship between concentric impulse and time to 5 m observed in females was linear ($R^2 = 0.487$), but this relationship was affected by other factors outlined in Table 4-3.

Concentric impulse was a statistically significant predictor in all three regression models (Table 4-3). The best prediction equations for time to 5 m in females and males were as follows:

Females: T5 m (s) = 2.103 – 0.003 (concentric impulse) – 0.209 (RSImod) + 0.0002 (concentric mean power)

Males: T5 m (s) = 2.645 – 0.010 (concentric impulse) + 0.00002 $(\text{concentric impulse})^2$

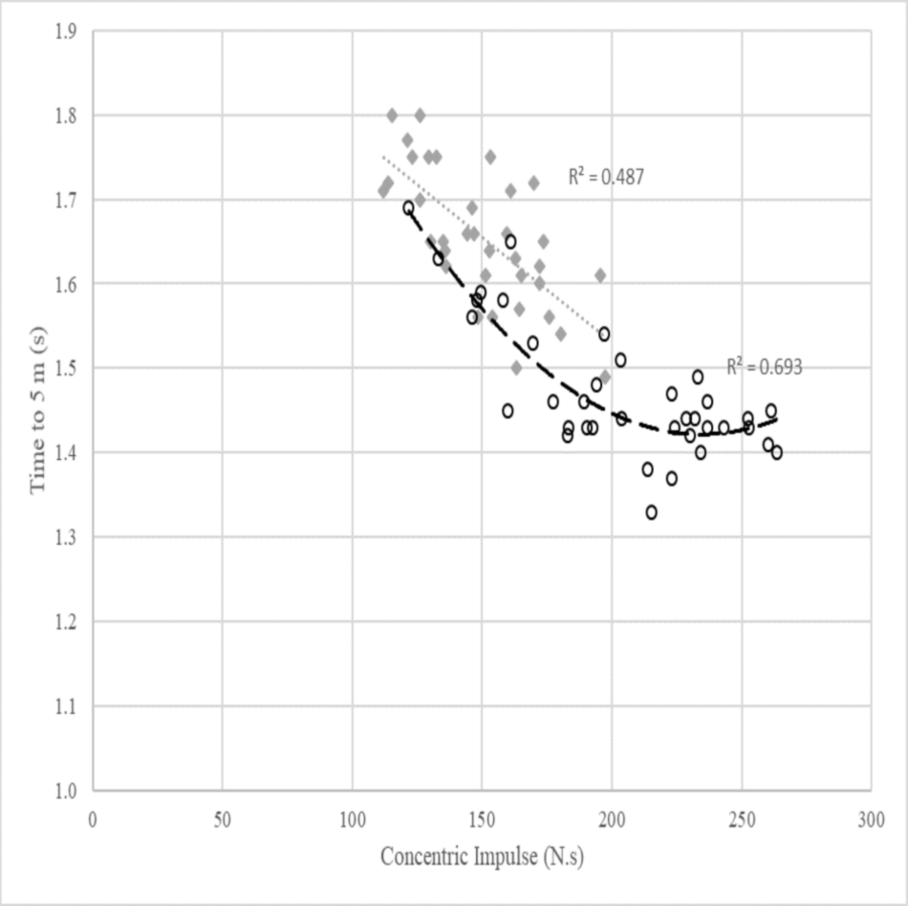

Figure 4-2. Relationship between concentric impulse (N.s) against time to 5 m (s) across females and males. Poly means polynomial regression to order 2, i.e. quadratic. The grey dotted line and diamond markers represent the linear relationship between concentric impulse and time to 5 m in females. The dashed line with circle markers represents the quadratic relationship between concentric impulse and time to 5 m in males.

Table 4-3. Multiple linear regression models to predict swim start time (s) to 5 m performance in females, males and both females and males combined.

		% contribution	Beta coefficient (95 % CI)	*p*-value
All	**Concentric Impulse (N.s)**	70.4	-0.002 (-0.002 to -0.001)	< 0.001
	Sex (Females)	5.4	0.065 (0.028 to 0.102)	0.001
	RSImod (m/s)	1.5	-0.084 (-0.164 to -0.004)	0.040
	Constant		1.882 (1.790 to 1.974)	< 0.001
	R^2 (SEE)		0.773 (0.059)	
Females	**Concentric Impulse (N.s)**	51.6	-0.003 (-0.004 to -0.002)	< 0.001
	RSImod (m/s)	9.5	-0.209 (-0.315 to -0.104)	< 0.001
	Concentric Mean Power (W)	7.8	0.0002 (0.00004 to 0.0003)	0.010
	Constant		2.103 (1.986 to 2.219)	< 0.001
	R^2 (SEE)		0.689 (0.047)	
Males	**Concentric Impulse (N.s)**	53.6	-0.010 (-0.015 to -0.005)	< 0.001
	Concentric Impulse^2 (N.s)^2	12.3	0.00002 (0.00001 to 0.00003)	0.001
	Constant		2.645 (2.167 to 3.124)	< 0.001
	R^2 (SEE)		0.659 (0.055)	

SEE = standard error of estimate

4.5.2 TIME TO 15 M

The scatterplot in Figure 4-3 shows a quadratic relationship between SJ concentric impulse and time to 15 m in males ($R^2 = 0.746$). For a fast time to 15 m in males, a minimum concentric impulse production of around 230 N.s is required. However, similar to Figure 4-2, the relationship between concentric impulse and time to 15 m observed in females was linear ($R^2 = 0.651$) but this relationship was also affected by other factors presented in Table 4-4.

The SJ concentric impulse was also the main significant predictor in all three regression models of the time to 15 m (Table 4-4). The best regression models were as follows:

Females: T15 m (s) = 9.303 – 0.030 (concentric impulse) + 0.035 (body mass) + 0.0002 (concentric RPD) – 1.714 (RSImod)

Males: T15 m (s) = 11.188 – 0.033 (concentric impulse) – 0.048 (age) + 0.00007 (concentric impulse)^2

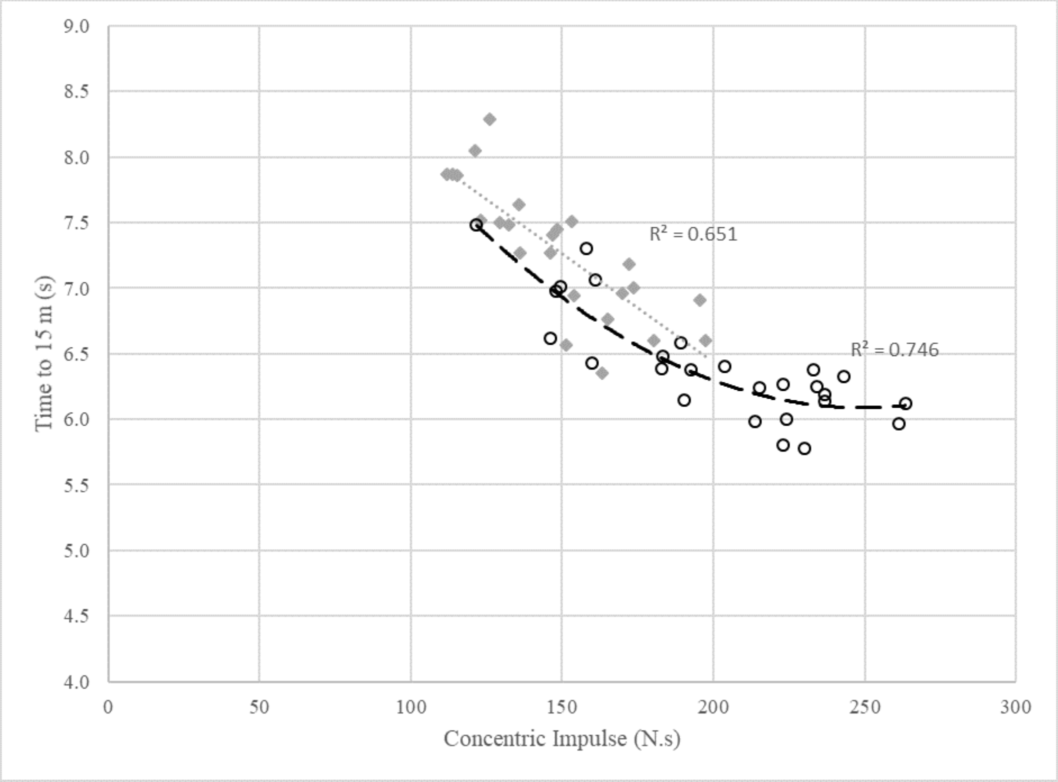

Figure 4-3. Relationship between concentric impulse (N.s) against time to 15 m (s) across females and males. Poly means polynomial regression to order 2, i.e. quadratic. The grey dotted line and diamond markers represent the linear relationship between concentric impulse and time to 15 m in females. The dashed line with circle markers represents the quadratic relationship between concentric impulse and time to 15 m in males.

Table 4-4. Multiple linear regression models to predict swim start time (s) to 15 m performance in females, males and both females and males combined.

		% contribution	Beta coefficient (95 % CI)	p value
All	**Concentric Impulse (N.s)**	76.1	-0.008 (-0.011 to -0.004)	< 0.001
	Age (years)	3.5	-0.052 (-0.087 to -0.018)	0.004
	Sex (female)	3.0	0.362 (0.151 to 0.572)	0.001
	Constant		9.074 (8.503 to 9.646)	< 0.001
	R^2 (SEE)		0.826 (0.278)	
Females	**Concentric Impulse (N.s)**	65.1	-0.030 (-0.041 to -0.020)	< 0.001
	Body mass (kg)	9.3	0.035 (0.006 to 0.064)	0.020
	Concentric RPD (W/s)	4.9	0.0002 (0. 00006 to 0.0003)	0.004
	RSImod (m/s)	4.8	-1.714 (-3.215 to -0.213)	0.027
	Constant		9.303 (8.398 to 10.208)	< 0.001
	R^2 (SEE)		0.841 (0.225)	
Males	**Concentric Impulse (N.s)**	66.6	-0.033 (-0.058 to -0.008)	0.011
	Age (years)	9.4	-0.048 (-0.086 to -0.010)	0.016
	Concentric Impulse^2 $(\text{N.s})^2$	4.7	0.00007 (0.000007 to 0.0001)	0.031
	Constant		11.188 (8.975 to 13.401)	< 0.001
	R^2 (SEE)		0.807 (0.205)	

SEE = standard error of estimate

4.6 DISCUSSION

The present study revealed that several lower body force-time characteristics, in particular concentric impulse, were significantly related to swim start performance in national and international level swimmers. However, when these analyses were performed for each sex individually, several differences in the prediction of swim start performance were observed. These sex-related differences in key force-time characteristics suggest that strength and conditioning programs and regular monitoring of performance may need to be tailored to male and female swimmers.

In the swim start, swimmers have to apply large forces rapidly on the start block to maximise horizontal take-off velocity, which in turn allows them to travel farther horizontally in the air before entering the water (19). This task demand is consistent with the impulse-momentum relationship, whereby an impulse (the product of force and time of force application) needs to be generated to cause a change in momentum (i.e. velocity) of the system (120). An analysis by Tor et al. (121) of the above water parameters in the swim start have found that take-off velocity and time on block were key predictors of swim start performance as assessed by time to 15 m using the OSB11 start block. Strong positive correlations between peak forces in the countermovement jump and peak forces on the OSB11 start block have also been reported by Cossor and colleagues (122). Thus, to be able to achieve a high take-off velocity, a swimmer needs to be able to apply high forces/ impulses off the starting block. Given that the swim start is mainly a concentric only movement, the findings of the present study further emphasise the important association between a swimmers' ability to produce impulse in the SJ and swim start performance.

It was expected that the current study would demonstrate a stronger prediction to 5 m than 15 m in the swim start. This hypothesis was based on how the movement pattern in the SJ is similar to the initial push-off in the block phase as well as the findings of Garcia-Ramos et al. (72) and Benjanuvatra et al. (73), who reported a significant correlation in take-off velocity (72) and jump height (73) in the SJ to 5 m (r =-0.56 and r =-0.92 respectively) but not 15 m. In contrast to this initial hypothesis, the current study demonstrated that the SJ force-time variables explained a greater amount of variance in time to 15 m than time to 5 m. Results of the current study were also consistent with Garcia-Ramos et al. (77) who observed that the correlations between jump height and swim start performance were greater for the time to 15 m (r = -0.67) than time to 5 m (r = -0.55) using the kick start technique. Such equivalence in the literature was surprising, but it is possible that these contrasting findings from the current study to the limited literature could be attributed to a variety of between study differences, including the swim start technique and start block, as well as the sample size and homogeneity of participants included in the previously published studies. The current study utilised the kick start technique on the OSB11 start block, whereas Benjanuvatra et al. (73) and Garcia-Ramos et al. (72) utilised the grab start and track start, respectively. In addition, both of these studies included only female swimmers and had substantially smaller sample sizes (*n* = 20 and *n* = 7), whereas the current study utilised a mix of male and female swimmers, with a larger sample size for both time to 5 m (*n* = 72) and 15 m (*n* = 50). As previously mentioned, the underwater phase is a key parameter in swim start performance, as a swimmer spends the highest percentage of the start in the underwater phase for all swim strokes (12, 25, 121). Garcia-Ramos et al. (72) have suggested that swimmers require high levels of lower body strength and power to maximise their underwater kick performance. Therefore, it is possible that the stronger prediction in time to 15 m than 5 m in this study and the study by Garcia-Ramos et al. (77) may reflect the commonality in lower body force-time characteristics required for the block phase with the kick start technique and the undulatory kicks performed during the underwater phase.

Another focus of this study was examining potential sex-related differences in the force-time characteristics that may underpin swim start performance in high-performance swimmers. While concentric impulse was the strongest predictor for time to 5 m and 15 m in both males and females, the current study identified some differences between the sexes with respect to the predictors of time to 5 m and 15 m. For a quick time to 5 m and 15 m in males, a minimum concentric impulse of 200 – 230 N.s appears required, with any additional impulse production not being associated with a reduction in swim start times for most male swimmers. However, it is worth noting that within the dataset, there appear to be some athletes whose performance sits outside the generalised trend, showing increased performance gains from additional concentric impulse about the level at which most individuals are deriving no further benefit (Figure 4-2 and 4-3). Nevertheless, these findings tend to suggest that for male swimmers capable of producing greater than 230 N.s of impulse, it might be most beneficial for their strength and conditioning program to focus on improving their rate of force development, as it is possible that developing this high level of impulse in a shorter block time is required to further improve their swim start performance.

In contrast to the results for the male swimmers, which had concentric impulse as the sole contributing force-time variable from squat jumps, the swim start performance to 5 m and 15 m for females were also influenced by other factors such as RSImod, mean power and concentric RPD. A few possible explanations for the differing strategies could be attributed to maximal strength capacity, load-velocity and neuromuscular capability between both sexes. Although lower body muscular strength was not measured in the current study, maximal strength has been shown to be a limiting factor in jumping ability and other lower body measure of explosive strength (123, 124). Previous research has demonstrated that males possess greater maximal strength and ability to produce greater velocities at the same percentage of one repetition maximum than their female counterparts (112, 125). When comparing the force-time curves in the countermovement jump between sexes, previous research has reported that the male and female differences in countermovement jump height were attributed to force characteristics and not temporal characteristics of the force-time curve (125, 126). This suggests that both sexes possess similar abilities to express forces, but the primary difference in jumping ability was due to the rate and magnitude of force production during both peak eccentric and concentric force production, which may be explained by differences in muscle architecture and structure, such as thickness and size of muscle fibers (111). These sex related differences might therefore explain some of the differing swim start predictors identified in the present study.

Previous studies have suggested that there is a trade-off between time spent on the starting block and take-off velocity, as the likelihood of greater impulses being produced with greater block times (26, 127, 128). From a practical standpoint, a possible strategy to increase impulse generated on the starting block without excessively increasing the time of force application is to increase muscular strength and rate of force development qualities of the lower body through heavy resistance training, ballistic concentric-dominant exercises (i.e. jumps without a preceding eccentric contraction) and plyometric training (10, 129). Heavy resistance training has been shown to increase power production, rate of power development, rate of force development and increases in muscle fiber cross-sectional area and neuromuscular activity (130). Ballistic/ plyometric training may improve the transfer of maximal strength to power production and rate of force development (124), thereby significantly improving swim start performance metrics including time to 5 m, take-off velocity and impulse (19, 56, 83). From a monitoring perspective, if a swimmer possesses the concentric impulse production required but has slow start times to 5 m and 15 m, improving rate force development and/or assessing technical factors such as angle of entry, degree of streamline, hydrodynamic drag and underwater propulsion may be imperative to maximise strength transfer to the swim start and ultimately swimming performance (26). Thus, swimmers should be concurrently performing lower body strength and conditioning program that includes some mixture of strength, ballistic and/or power training while ensuring sufficient practice of the swim start to optimise the transfer of their strength and conditioning program in improving swim start performance (24).

There are some limitations in this study that could be addressed in future research. Firstly, baseline strength was not measured in any of the participants. Future work should examine the relationship between lower body force-time characteristics in strength matched swimmers and its effect on swim start performance to elucidate if differences between male and female swimmers were due to muscular strength or neuromuscular differences (131). Secondly, due to the difference in sample sizes for the different swim strokes in the current study, it would be worth exploring what force-time characteristics underpin swim start performance in other swim strokes in comparison to the front crawl, and if there are different neuromuscular qualities required for swim start performance in the different swim strokes.

4.7 CONCLUSION

In summary, this study has identified bodyweight squat jump concentric impulse as a key lower body force-time characteristic that was significantly related to swim start performance in high-performance swimmers. As impulse is the product of the ground reaction force and time of force application, it is integral for a swimmer to have the requisite ability to generate a high level of concentric impulse in a relatively short amount of time. Due to the different strength of the prediction equations, it appears that male and female swimmers utilise somewhat differing strategies during the swim start. While it is unknown if this is predominantly a result of the differences in muscular strength and force producing capacity between sexes, our results highlight the need for strength and conditioning coaches to consider individualising training programs to enhance swim start performance and ultimately swimming performance between sexes.

CHAPTER 5: ON-BLOCK MECHANISTIC DETERMINANTS OF START PERFORMANCE IN HIGH PERFORMANCE SWIMMERS

5.1 PREFACE

The results presented in Chapter 4 identified the squat jump (SJ) lower body force-time characteristics that were most predictive of swim start performance as assessed by times to 5 m and 15 m. While such results have applications to the assessment and strength and conditioning programs for high performance swimmers, it is also imperative to identify the most important on-block lower body force-time characteristics, and how forces are sequenced for an optimal block phase. This knowledge would assist in the assessment of swim start performance, as well as the prescription of technical drills and/or strength and conditioning programs to improve start performance.

In this chapter, a cross-sectional study design using linear mixed modelling and multiple linear regression were used to analyse start trials from as many as 152 swimmers using the KiSwim Performance Analysis System. This methodology was performed to identify which block outcome kinetic measure have the greatest relationship to 15 m start time, and how lower and upper body forces are sequenced in the block phase.

The findings of this chapter informed the block outcome kinetic variables used for analysis in Chapters 6 and 7.

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5.2 ABSTRACT

This study aimed to 1) identify what starting block outcome kinetics have the greatest relationship to 15 m start time; 2) investigate key mechanistic determinants of the block phase and how these forces are sequenced. One hundred and fifty-two high level competitive swimmers were included in the study. Linear mixed modelling identified four on-block outcome kinetic variables (work, average power, horizontal take-off velocity, and average acceleration) as having a very large relationship (R^2 = 0.79 - 0.83) to 15 m start time, with average power having the most substantial impact. On-block force sequencing started with the rear leg, followed by upper limb grab forces and the front leg. Further exploration of underlying determinants was performed for average power and horizontal take-off velocity of the centre of mass. Multiple linear regression identified grab resultant peak force, rear resultant average force, front horizontal peak force, and resultant peak force as significant predictors of average power (R^2 = 0.88). Horizontal take-off velocity was predicted using the same variables, apart from the inclusion of rear horizontal peak force instead of rear resultant average force (R^2 = 0.73). These findings may influence how strength and conditioning and skill acquisition interventions are designed to improve swim start performance.

Key words: swimming, swim start, block phase, force plate, kinetics

5.3 INTRODUCTION

Competitive swimming races can be decided by the smallest of margins (7). As an example, at the 2016 Olympic Games, 0.01 seconds decided medal outcomes in the men's 50 m freestyle, 100 m butterfly and 200 m backstroke events, along with the women's 100 m freestyle, 100 m backstroke and 4x100 m medley relay. Given how close competitions results can be, swimmers must maximise performance in every aspect of the race to achieve success. Analysis of competition races generally divides the race into four segments: the start, the free swim component, turns and the finish (5, 6, 12). The swim start is defined as the time from the start signal to the swimmer's head crossing the 15 m mark, with this segment further broken down into the block, flight and underwater phases (12). Although a swimmer spends the highest percentage of the start in the underwater phase, the block phase is reported to have the most impact on the duration of the flight and subsequently the underwater phase (20). A block phase resulting in greater horizontal take-off velocity will tend to produce greater flight distance and a higher velocity on entry into the water (9, 132).

The OSB11 (OMEGA, Zurich, Switzerland) features an adjustable kick plate angled at 30° to the front plate that can be placed in one of five different positions, each at a set distance (35 mm intervals) along the length of the starting platform. This starting block led to the development of the kick start technique, which is currently used by swimmers in international competitions (26). The rationale for this design was that the additional kick plate allows for an increased duration of horizontal force application on the blocks, which increases horizontal impulse and horizontal velocity at take-off, and a reduced time to 5 m and 7.5 m (30).

Much of the biomechanical research on the block phase has explored kinetic and kinematic outcome measures that relate to swimming start performance (20, 63, 132). In an attempt to determine the most important on-block measures for swim start performance, Garcia-Ramos et al. (63) examined 18 on-block variables, identifying average horizontal force, horizontal take-off velocity, resultant take-off velocity and average horizontal acceleration as significantly correlated to time to 15 m in 21 competitive female swimmers. However, relatively little is known in terms of how the on-block kinetics influences the kinematic descriptors of the block phase, such as horizontal take-off velocity and average horizontal acceleration (133).

Previous kinetic research examining force production on the starting block has highlighted the different roles that the front and rear leg have during the block phase (20, 128, 134). Slawson et al. (20) observed higher horizontal and vertical peak forces were associated with better block performance, as assessed by shorter block time, higher take-off velocities and greater entry distances. In addition, Ikeda et al. (134) and Takeda et al. (128) identified the early development of large force impulses from the hands and rear leg contributed towards the horizontal take-off velocity off the blocks.

Current limitations of previous studies are the relatively small sample sizes (*n* = 11 – 46), and the examination of either the relationship of mechanistic variables to block performance measures (20, 128, 134) or outcome block kinetic measures to start performance in female swimmers (63) but not both elements within the same population incorporating both sexes. A deeper understanding of the underlying kinetic and temporal sequencing of these forces on the starting block in a larger sample of competitive swimmers (than the 11 – 46 used in previous studies) may assist in the assessment of swim start performance as well as the prescription of technical drills and/or strength and conditioning programs to improve starting performance.

Therefore, the two aims of this study were: 1) Identify what block outcome measures have the greatest impact on front crawl 15 m kick start time in a large sample of both male and female high performance swimmers; 2) Identify and describe the sequencing of key on-block mechanistic variables that contribute to block outcome measures identified in part one and how these forces are sequenced. We hypothesised that 1) horizontal take-off velocity would be the strongest predictor of 15 m start time and 2) average force (impulse) values would be more important than peak forces in determining contributions of the rear leg, front leg, and arms to on-block performance with these relationships existing independent of sex.

5.4 MATERIALS AND METHODS

5.4.1 STUDY DESIGN

A cross-sectional study design was conducted to quantify the relationship between starting block outcome measures from instrumented force plates to swim start performance as assessed by 15 m start time.

5.4.2 PARTICIPANTS

One hundred and fifty-two athletes with at least two years of competitive experience were included in the study. To contextualise the level of participants studied, state developmental level was comprised of swimmers who competed at the most recent national championships. Elite level comprised of swimmers who had competed internationally in either the Olympics, Commonwealth Games or World Championships. All participants provided written informed consent to participate in the study, which was conducted in accordance with the Declaration of Helsinki and approved by the Bond University Human Research Ethics Committee.

5.4.3 METHODOLOGY

Ventral starts were selected from a database of start trials tested between December 2015 and December 2019 using the Kistler Performance Analysis System – Swimming (KiSwim, Kistler Winterthur, Switzerland; Kistler 2020) . Participants performed maximal 15 m ventral starts with their main swim stroke (front crawl, butterfly, breaststroke). Trials were started as per competition conditions and swimmers were instructed to swim to a distance past the 15 m mark, to ensure that representative 15 m start times were obtained (115).

In Section 1, to avoid the potential confounding influence of speed differences in both the underwater and swim phases of the butterfly and breaststroke, only front crawl was included in the time to 15 m analysis as it comprised majority of the participants (n = 101) (136). Multiple trials were included in the analysis, with a total of 53 males (22.6 ± 3.2 years, 78.7 ± 9.6 kg) and 48 females (21.0 ± 3.8 years, 64.7 ± 6.1 kg) performing a total of 758 front crawl swim starts. As the block phase for all ventral starts are similar, front crawl (n = 56), breaststroke (n = 19), and butterfly (n = 19) were included in Section 2. Swimmers had to have at least three starts to 15 m in the database, with the fastest three swim starts of each swimmer selected for analysis. Forty-nine males (23.5 ± 2.9 years, 80.5 ± 7.0 kg) and 45 females (23.5 ± 3.7 years, 66.3 ± 5.7 years) with a total of 282 swim starts were included in the analysis in Section 2.

5.4.4 EQUIPMENT

The KiSwim utilises an instrumented starting block with three force plates, constructed to match the dimensions of the Omega OSB11 block (KiSwim Type 9691A1; Kistler Winterthur, Switzerland; Figure 5-1A). The force plates were constructed to collect front leg and arms (front plate) and rear leg forces (kick plate) separately (Figure 5-1B and 5-1C). The grab bar and the front plate were separated by a 2 mm gap to distinguish the grab forces from the arms and the front leg force production (137). Time to 15 m was collected using a calibrated high-speed digital camera (100 fps) positioned 1.3 m underwater and perpendicular to the swimmer. The time to 15 m was defined as the period from the starting signal until the apex of the swimmers' head passed the 15 m mark (115). An Infinity Start System (Colorado Time Systems, Loveland, Colorado, USA) provided an audible starting signal to the athletes synchronised to the KiSwim system. All KiSwim variables are described in Table 5-1, with definitions provided in Appendix 10.

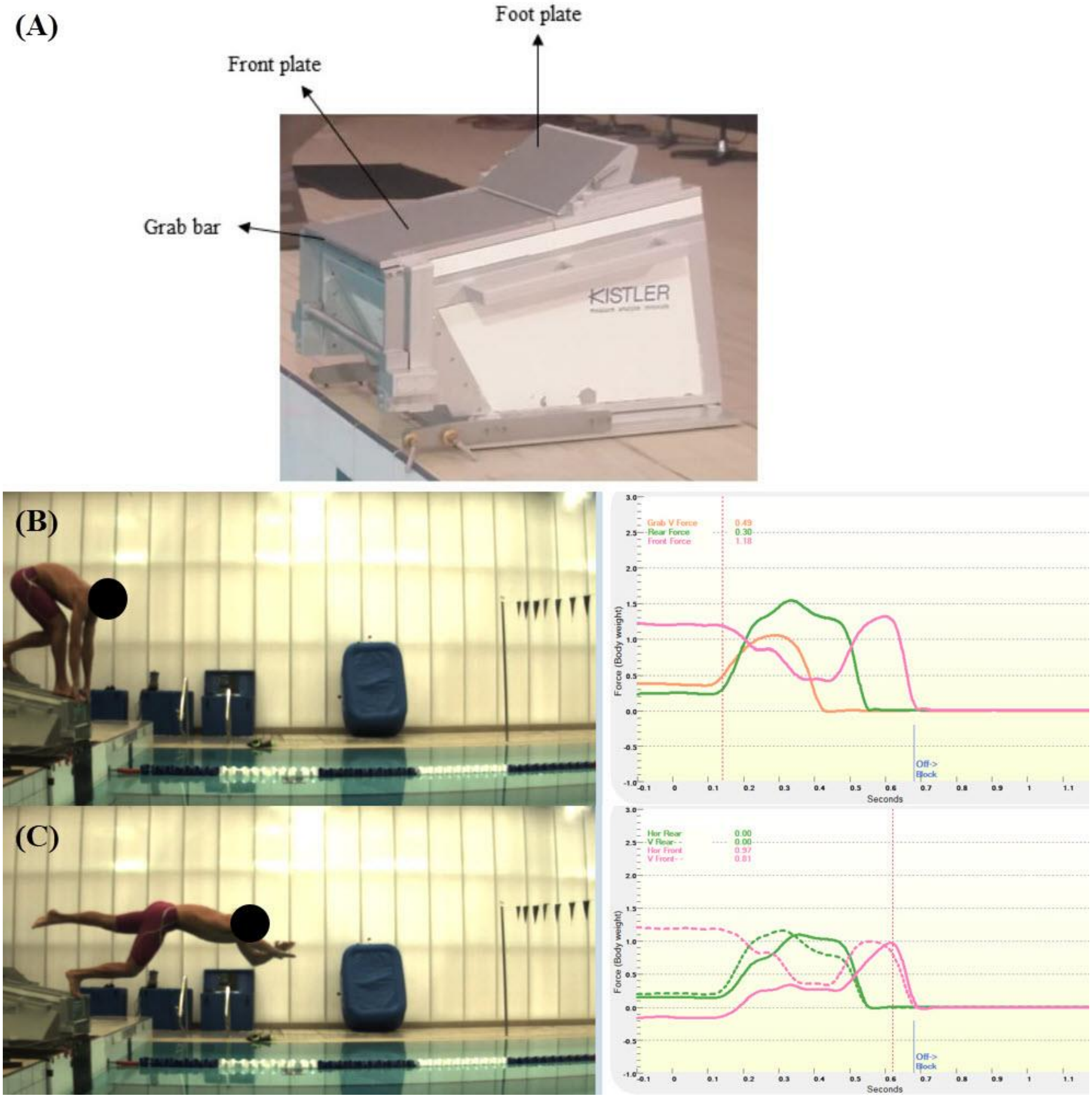

Figure 5-1. (A) The KiSwim instrumented starting block with three force plates. The foot plate, front plate and grab bar allows assessment of the rear leg, front leg, and hand forces, respectively. (B) Starting position of a swimmer on the instrumented starting block and the force profile of the grab forces from the arms (solid orange line), rear leg (solid green line) and front leg forces (solid pink line) (C) Swimmer taking off from the starting block and the force profile of the horizontal front (solid pink line), vertical front (dashed pink line) leg forces and horizontal rear (solid green line), vertical rear (dashed green line) leg forces. Photograph by the author.

Table 5-1. Kinetic and kinematic parameters and split times derived from the KiSwim Performance Analysis System.

Reaction time	Key movement timing events (expressed as a percentage of block time)	On-block force application (all variables are expressed per body mass and as a percentage of block time)	On-block outcome kinetics and kinematics	Performance times
Time to 1st move (s)	Hands off (s)	Horizontal peak force (N)	Average power (W/kg)	Time to 5 m, 7.5 m, 10 m, 15 m (s)
1st move rear (s)	Toe off rear (s)	Vertical peak force (N)	Work/kg (J/kg)	
1st move grab (s)		Resultant peak force (N)	Horizontal take-off velocity (m/s)	
1st move front (s)		Front horizontal peak force (N)	Average acceleration (m/s/s)	
		Front vertical peak force (N)	Resultant average force (N)	
		Front resultant peak force (N)	Vertical take-off velocity (m/s)	
		Front resultant average force (N)	Resultant take-off velocity (m/s)	
		Rear horizontal peak force (N)	Take-off angle (°)	
		Rear vertical peak force (N)		
		Rear resultant peak force (N)		
		Rear resultant average force (N)		
		Grab resultant average force (N)		
		Grab resultant peak force (N)		
		Peak power (W/kg)		

5.4.5 STATISTICAL ANALYSIS

Descriptive statistics are reported as mean ± SD for normally distributed continuous variables and frequency (%) for categorical variables. Normality was checked using normal Q-Q plots and the Shapiro-Wilk test. In Section 1, a linear mixed model approach including sex, race suit and front crawl as fixed effects and participant as a random effect was used to predict time to 15 m with the four on-block kinetic outcomes (work, average power, horizontal take-off velocity, and average acceleration). In Section 2, a multiple linear regression model was fit using a backward stepwise approach to predict two of the four on-block kinetic outcomes (i.e. average power and horizontal take-off velocity) using the on-block outcome kinetics variables in Table 5-1. The Akaike's information criterion was used as a measure of goodness of fit for the resulting models which were then assessed for multicollinearity using variance inflation factor (VIF) values. Variables with VIF values > 5 were examined and values which were resultant forces were removed in preference for maintaining the vertical or horizontal components. The assumptions of normality, linearity and homoscedasticity of residuals were verified. Results of the regression modelling are presented in terms of unstandardised coefficients, the 95 % CI and *p*-values, along with the R^2 and residual standard error. Data were analysed with statistical software R version 3.5.3, with *p*-values < 0.05 indicating statistical significance.

5.5 RESULTS

For clarity, the results are separated into two parts. The first section details the results of the relationship of the on-block outcome measures outlined in Table 5-2 to time to 15 m. The second section consists of a multiple linear regression that describes which on-block kinetic variables are potential predictors of the outcome variables identified in Section 1.

5.5.1 SECTION 1

The outcome kinetic variables were ranked by their marginal R^2 value, with males having a faster start time to 15 m than females ($p < 0.001$) (Table 5-2). To illustrate which variables could affect a meaningful change in time to 15 m, a change of one standard deviation of each variable was applied and resulting change in predicted time to 15 m was calculated. All 4 outcome variables had a significant relationship to time to 15 m ($R^2 = 0.79 – 0.83$) (Table 5-2). Both average power and average acceleration presented a quadratic relationship to time to 15 m, while horizontal take-off velocity and work had a linear relationship to time to 15 m. Modelling indicated that a one standard deviation increase in average power reduced time to

15 m by 0.20 s (3.2 %) and 0.17 s (2.4 %) for an average male and female swimmer, respectively. In comparison, equivalent changes in the other three outcome variables examined are expected to produce improvements of 1.8 – 2.5 % for males and 1.7 – 2.1 % for females.

Table 5-2. Outcome kinetic variables ranked by marginal R2 value with male and female (means and standard deviations) with predicted change in time to 15 m based on an addition of 1 standard deviation to each variable.

Block outcome variables	**Males**					**Females**			
			Predicted change in time to 15 m based on an addition of 1 SD				Predicted change in time to 15 m based on an addition of 1 SD		
	Marginal R^2	Mean ± SD	- 1 SD	Mean time to 15 m	+ 1 SD	Mean ± SD	- 1 SD	Mean time to 15 m	+ 1 SD
Work (J/kg)	0.83	15.61 ± 1.10	6.43	6.28	6.13	13.44 ± 0.99	7.24	7.11	6.98
Average Power (W/kg)	0.82	22.03 ± 2.37	6.50	6.28	6.08	17.90 ± 1.64	7.30	7.11	6.94
Horizontal take-off velocity (m/s)	0.79	4.63 ± 0.20	6.39	6.28	6.17	4.24 ± 0.20	7.23	7.11	6.99
Average Acceleration (m/s^2)	0.79	6.52 ± 0.56	6.45	6.28	6.12	5.65 ± 0.47	7.27	7.11	6.96

Following the results in Section 1, average power and horizontal take-off velocity were chosen for the multiple linear regression models in Section 2 due to the following reasons:

1) While all four variables had a very high marginal R^2, when considering the influence of the same relative change (one standard deviation) on performance, average power had the greatest potential effect on time to 15 m.
2) Horizontal take-off velocity has been consistently identified as an on-block variable that is most related to time to 15 m (32, 63). Horizontal take-off velocity is also the most accessible block outcome metric examined in this paper that can be assessed in an applied training environment, whereby it can be determined using video analysis rather than requiring specialised force instrumentation. The combination of these two factors was justification for its inclusion in the second level of analysis.

5.5.2 SECTION 2

A multiple linear regression including rear resultant peak force, front horizontal peak force, grab resultant peak force and rear resultant peak force explained 88 % of the variance in average power (Table 5-3). The model for horizontal take-off velocity mainly used the same variables, apart from the inclusion of rear horizontal peak force instead of resultant peak force for a slightly lower proportion of the variance explained (73 %).

Table 5-3. Multiple linear regression models to predict average power (W/kg) and horizontal take-off velocity (m/s).

		Beta coefficient (95 % CI)	*p*-value
Average power (W/kg)	**Grab resultant peak force (N/BW)**	2.04 (1.47 to 2.61)	< 0.001
	Rear resultant average force (N/BW)	17.83 (15.67 to 19.99)	< 0.001
	Resultant peak force (N/BW)	4.17 (3.62 to 4.72)	< 0.001
	Front horizontal peak force (N/BW)	7.65 (6.13 to 9.16)	< 0.001
	Constant	- 4.97 (- 6.24 to - 3.71)	< 0.001
	R^2	0.88	
	Residual standard error (degrees of freedom)	1.01 (277)	
Horizontal Take-off velocity (m/s)	**Grab resultant peak force (N/BW)**	0.30 (0.22 to 0.37)	< 0.001
	Rear resultant average force (N/BW)	1.14 (0.83 to 1.45)	< 0.001
	Rear horizontal peak force (N/BW)	0.62 (0.45 to 0.79)	< 0.001
	Front horizontal peak force (N/BW)	0.72 (0.49 to 2.60)	< 0.001
	Constant	2.44 (2.27 to 2.60)	< 0.001
	R^2	0.73	
	Residual standard error (degrees of freedom)	0.14 (277)	

Average time spent on the starting blocks for male and female swimmers were 0.68 s and 0.72 s respectively. Figure 5-2 depicts the relative timing of the five key deterministic on-block variables described in Table 5-3. Rear resultant average force, which represents total force application from the rear leg, initiates first at ~15 % of block time, continuing through to rear toe-off at ~80 % of block time. Grab resultant peak force, observed between 25 – 50 % of block time, is the other key variable occurring in the first half of the block phase. Rear horizontal peak force and resultant peak force occur in sequence between 60 – 80 % of block time, aligned with late rear leg drive. Front horizontal peak force occurs between 88 – 95 % of block time, during single leg drive following rear toe-off.

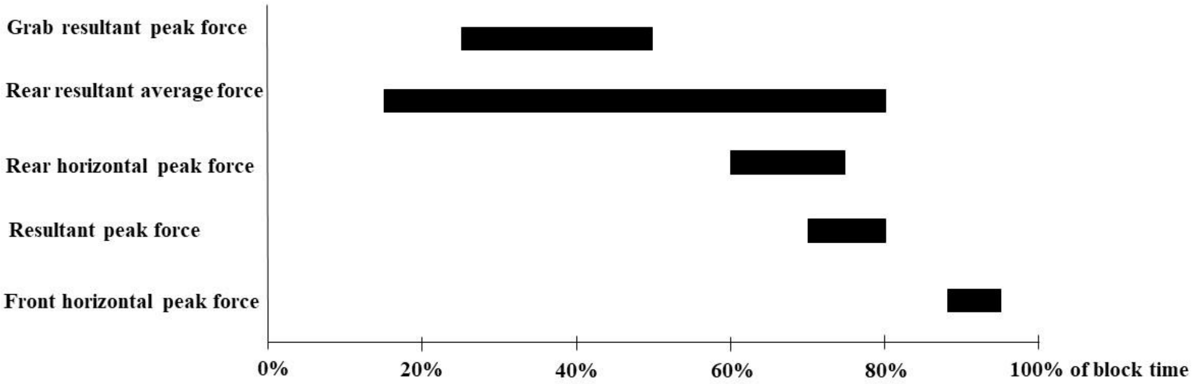

Figure 5-2. Sequencing of key on-block kinetic predictors identified in the multivariate regression models, presented as a percentage of total block time. Bars represent the range of time in which each variable is typically observed.

5.6 DISCUSSION

5.6.1 SECTION 1

This study identified all four on-block outcome kinetic variables (work, average power, horizontal take-off velocity, and average acceleration) as having a very large relationship ($R^2 = 0.79 – 0.83$) to swim 15 m start time. The very high shared variance between all the on-block outcome variables examined and time to 15 m further supports how important the on-block phase is, despite only accounting for 11 % of the total time to 15 m (9, 20). These results partially support our hypothesis of horizontal take-off velocity as the strongest predictor to start time to 15 m. Although all four variables had strong relationships to performance, it was notable that the time-relative measures (average power and average acceleration), had a larger relative effect on start performance than the measures for which rate of development is not a factor (total work and horizontal take-off velocity).

As the swim start aims to translate the body over a set horizontal distance in the shortest amount of time (i.e., a swimmer must perform a specific amount of work in the desired direction in the least possible time), it seems relatively intuitive that the ability to produce power (move the centre of mass anteriorly in the shortest amount of time) would be an essential determinant of swim start performance. Average power provides a measure that accounts for a swimmer's change in velocity and the time taken to achieve this change (i.e., rate of change in kinetic energy) (138), with the time-relative nature being an important differentiation from other block performance variables such as total work and take-off velocity. However, these findings are somewhat at odds with previous research, which identified both average acceleration and horizontal take-off velocity as significant predictors of time to 15 m, with horizontal take-off velocity having a much stronger relationship than average acceleration (80 % and 58 % respectively) (32, 63). These differences may be linked to the different samples included in the studies, such as participant number, performance level of the swimmer or technical proficiency in the swim start. For example, Tor et al. (32) used retrospective data from a mix of elite male and female swimmers ($n = 52$) in comparison to Garcia Ramos et al. (63), who recruited 21 female national level swimmers in their study.

An additional finding of note from the current analysis, which may relate to the issue of technical ability, is the different overall relationship between the time-relative block outcome measures (average power and average acceleration), and those not rate-adjusted block outcome measures (work and horizontal take-off velocity). Our analysis identified that while work and horizontal take-off velocity displayed a linear relationship with time to 15 m, average power and average acceleration exhibited a quadratic relationship. This pattern meant that at the average start performance levels observed in this study, a swimmer would expect a bigger improvement in time to 15 m from the same relative change in average power or acceleration than from work or horizontal take-off velocity. These results suggest that rate of force development during the block phase should be a key focus for most high-level swimmers if they wish to reduce their start times. However, given the nature of quadratic relationships, there may be a leveling off effect towards the outer ranges of average power and average acceleration production, whereby greater levels of these time-relative block outcome measures may not necessarily lead to large reductions in the swimmers' time to 15 m performance.

5.6.2 SECTION 2

The purpose of this study was to establish the most appropriate approach to assess overall block performance and provide some mechanistic understanding of how forces on the block are sequenced. As identified earlier, this next layer of the investigation was performed using two of the block outcome measures: average power, as the strongest predictor of time to 15 m, and horizontal take-off velocity, as the most practical measure in an applied setting. Based on this, grab resultant peak force, rear resultant average force and front horizontal peak force were identified as significant predictors of both average power and horizontal take-off velocity, since multiple linear regression models explained 88 % and 73 % of the variation in average power and horizontal take-off velocity, respectively. The inclusion of resultant peak force in the model for average power and the integration of rear horizontal peak force in the horizontal take-off velocity model was the point of differentiation between the two outcome variables.

Based on the impulse-momentum relationship, in which the impulse (product of force and time of force application) will determine the change in velocity, it was hypothesised that average rear leg, front leg and arm forces may be more important than their peak forces in determining block performance. Consistent with our findings, the literature suggests that a mixture of average (134) and peak forces (20) are key determinants of block performance. Such results may reflect the complexity of the swim start and indicate that while the ability to produce large forces and impulses on the starting blocks is a key aspect of block performance, swimmers may utilise different movement strategies to optimise their block performance. These different movement strategies used by individual athletes may be an example of the constraints led approach of dynamic systems theory. Specifically, any differences in the three level of constraint (individual, task, or environment) may contribute to differences in start performance such as time to 5 m or 15 m, as well as the kinematic and kinetic outputs that characterises the coordination patterns used during the swim start (139).

The findings in the current study highlight the importance of specific force metrics of the block phase for optimising performance in the swim start, with improvements in such force metrics made possible through technical and/or force generation (strength) development. From a technical perspective, another finding of this current study with potential applications to technical and strength training is how these different forces are sequenced. Rear resultant average force, which represents total force application from the rear leg drive, initiates first at ~15 % of block time, with this continuing through to rear toe-off at ~80 % of block time. This long duration of force application from the rear leg demonstrates the importance of the rear leg's role as one of the primary contributors to start performance (20, 128, 134). For example, higher rear leg forces have been associated with better swim start performance as assessed by the shortest time on the block, fastest horizontal take-off velocity, and furthest entry distance (20).

Identification of the grab resultant peak force in the present study is consistent with the findings of Takeda et al. (128), who identified the vital involvement of the upper limbs in contributing to horizontal take-off velocity in 11 competitive swimmers. Our results extend these findings by demonstrating that the upper limb forces on the front of the starting block are maximised in the first half of block time (25 – 50 %), during a period of early force development from the rear leg and initiation of the forward movement of the centre of mass. In a study examining the effects of an isometric pre-tension on jump performance, the use of an isometric pre-tension recorded significantly higher peak forces and rate of force development than a countermovement jump (140). The timing and importance of this peak grab force highlight the likely importance of the upper limbs' role in initiating movement by not only pulling on the starting blocks, but also by creating muscular pre-tension throughout the entire kinetic chain early in the swim start that may augment the lower body contribution to total force production.

Resultant peak force is the combination of forces measured from the front and back force plates, with this parameter occurring between 60 – 80 % of block time. During this period, both legs are driving hard on the blocks, with the front leg now being able to produce a posteriorly directed force that can assist in increasing the swimmer's horizontal impulse and take-off velocity. Forces from the front and rear leg have been found to be significantly different in the swim start (128, 134, 141). The front leg's primary propulsive role is in the final period of acceleration, with front horizontal peak forces occurring at ~88 % of block time. The latent production of forces of the front leg highlights the requirement in maintaining a strong push off from the rear leg to the front leg through till toe-off. Furthermore, the identification of peak horizontal forces from the front leg further emphasises the direction specificity of force production not only from the rear leg but also the front leg throughout the block phase. Another question of interest to strength conditioning coaches and sport scientists is how the different joints contribute to this sequential force production. Quantification of joint torques have identified that in the rear leg, extension torques at the hip and knee joint are initially produced, followed by ankle plantar flexion torque and a proximal to distal triple extension of the front leg (142). This sequencing of force outputs and joint torques has important implications for sports scientists and swim coaches undertaking technical work with swimmers, as well as for strength and conditioning coaches who may look to develop and incorporate resistance training exercises that better match the directional and sequencing requirements of the block start.

5.6.3 PRACTICAL APPLICATIONS

For an optimal block performance, swimmers should set themselves on the block by creating tension throughout the entire kinetic chain in the setup. Shortly after the start signal, high forces should be produced as quickly as possible on the rear kick plate. These high rear leg forces need to be maintained for as long as possible until the rear foot leaves the kick plate, with these rear leg forces complemented by the sequential activation of the upper body on the grab plate and finally the front leg on the front plate. Our results suggest a requirement for both technical ability and physical capability in swimmers, with the magnitude, direction, and timing of these forces important to optimise start performance. This has clear importance for sport scientists, swim coaches and strength and conditioning coaches in improving swimmers' block and swim start performance. Due to the curvilinear relationship that average power has with time to 15 m, the relative benefits of continuing to improve this may have diminishing returns on performance at higher output values. For example, swimmers who have lower power-generating ability, improving this should have a substantial effect. However, for highly trained swimmers who are already able to produce high levels of average power (a product of resultant forces, irrespective of orientation), focusing on orienting force application more horizontally on the starting blocks might be more beneficial.

5.7 CONCLUSION

In summary, this study has identified four block outcome kinetic variables (work, average power, average acceleration and horizontal take-off velocity) as strong predictors of swim start performance, with a one standard deviation change in average power having the greatest potential effect on time to 15 m in a larger sample of high performance swimmers. The practicality of horizontal take-off velocity in an applied setting has led us to develop a multiple linear regression model to identify key on-block mechanistic variables that contribute to both average power and horizontal take-off velocity. The underlying kinetic and temporal sequencing of forces on the starting block identified in this study highlights the direction and temporal specificity of horizontal force application on the starting block, with the rear leg having the highest contribution to block performance. Future research may explore how potential effects of factors including age, sex, and swim stroke may influence the sequencing of force and joint torque production in the block phase and the relationship to time to 15 m, as well as the chronic effects of strength and conditioning and/or skill acquisition interventions that focus on developing some of the on-block predictors of swim start performance identified in the present study.

CHAPTER 6: PUSHING UP OR PUSHING OUT – AN INITIAL INVESTIGATION INTO HORIZONTAL- VERSUS VERTICAL-FORCE TRAINING ON SWIMMING START PERFORMANCE: A PILOT STUDY

6.1 PREFACE

Given that swimmers have to take-off from the starting blocks in a direction that is primarily horizontal, there is a potential specificity involved in the direction of force application that should be utilised in dry-land resistance training sessions to enhance the swim start. The potential direction specificity of training (also referred to as the force-vector theory) has been examined in two jump/plyometric training studies (19, 56) and two acute post-activation potentiation (PAP) studies (81, 82) that were included in the systematic review (Chapter 3). However, a gap exists in relation to the knowledge of the force-vector theory of resistance training exercises and their impact on swim start performance using the OSB11 block currently used in competitive swimming. Therefore, this chapter aims to provide an understanding of a horizontal- versus vertical-force oriented emphasis resistance training program on swim start performance.

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6.2 ABSTRACT

The block phase in the swimming start requires a quick reaction to the starting signal and a large take-off velocity that is primarily horizontal in direction. Due to the principle of specificity of training, there is a potential benefit of performing a greater proportion of horizontal force production exercises in a swimmers' dry-land resistance training sessions. Therefore, the purpose of this pilot study was to provide an insight into the effects of a horizontal- (HF) versus vertical-force (VF) training intervention on swim start performance. Eleven competitive swimmers (six males (age 20.9 ± 1.8 years, body mass 77.3 ± 9.7 kg, height 1.78 ± 0.05 m) and five females (age 21.4 ± 2.0 years, body mass 67.5 ± 7.4 kg, height 1.69 ± 0.05 m)) completed two weekly sessions of either a horizontal- or vertical-force oriented resistance training program for eight weeks. Squat jump force-time characteristics and swim start kinetic and kinematic parameters were collected pre- and post-intervention. Across the study duration, the swimmers completed an average of nine swimming sessions per week with an average weekly swim volume of 45.5 ± 17.7 km (HF group) and 53 ± 20.0 km (VF group), but little practice of the swim start per week (*n* = 9). Within-group analyses indicated a significant increase in predicted 1RM hip thrust strength in the HF group, as well as significant increases in grab resultant peak force but reductions in resultant peak force of the block phase for the VF group. No significant between-group differences in predicted 1RM hip thrust and back squat strength, squat jump force-time and swim start performance measures were observed after eight weeks of training. Significant correlations in the change scores of five block kinetic variables to time to 5 m were observed, whereby increased block kinetic outputs were associated with a reduced time to 5 m. This may be indicative of individual responses to the different training programs. The results of this current study has been unable to determine whether a horizontal- or vertical-force training program enhances swim start performance after an eight-week training intervention. Some reasons for the lack of within and between group effects may reflect the large volume of concurrent training and the relative lack of any deliberate practice of the swim start. Larger samples and longer training duration may be required to determine whether significant differences occur between these training approaches. Such research should also look to investigate how a reduction in the concurrent training loads and/or an increase in the deliberate practice of the swim start may influence the potential changes in swim start performance.

Keywords: specificity of training, force-vector theory, resistance training, swimming, swim start

6.3 INTRODUCTION

The important role that muscular strength and power play in enhancing swimming performance has led to the widespread adoption of dry-land resistance training modalities into a concurrent training model for competitive swimmers (42, 44, 46). While much of the swimming strength and conditioning research has been on the free swim portion (42), there is now a greater focus on starts and turns since swimmers have to rapidly apply large forces on the starting block or wall to increase horizontal impulse and velocity (19, 143, 144).

Changes in the starting block and starting technique may have further increased the importance of lower body strength and power for swim start performance. The OSB11 start block, which was introduced by the International Swimming Federation in 2010, has an angled kick plate at the rear of the block that enables the swimmer to adopt a kick start technique (32). The additional kick plate allows for an increased duration of effective force application (i.e. greater horizontal force component) on the blocks, which can increase horizontal impulse and take-off velocity (30).

With the new OSB11 start block and kick start technique, the swim start may share some similarities to the sprint start in track and field regarding the starting position, importance of a quick reaction to the starting stimulus, and the need to produce large horizontal impulse on the starting blocks (145, 146). Analysis of the force-time characteristics of swimmers performing the squat jump has identified concentric impulse as a strong predictor of swim start performance as assessed by time to 5 m and 15 m (136). Further, near perfect correlations ($r > 0.90$) have been found between swim start performance and countermovement jump height or take-off velocity, with very large correlations for measures of maximal strength ($r = 0.7\text{-}0.9$) to swim start performance have been reported in a recent systematic review (108).

Three studies have utilised jump and plyometric exercise programs (19, 56, 83), two studies (24, 84) used a more general resistance training program, and one study (144) compared the effects of maximal strength resistance training to plyometrics. Despite the strength of this cross-sectional literature (108), there is relatively little research quantifying the chronic effects of resistance training on swim start performance. The three plyometric studies included adolescent (83) and national level swimmers (19, 56) who performed six to nine weeks of horizontal and vertical oriented plyometrics, which consisted of skips, bounds, hops and jumps twice a week. Significant improvements in time to 5 m and 5.5 m, take-off velocity and horizontal forces and impulse were observed because of these plyometric exercise programs (19, 56, 83). In contrast, the remainder of these plyometric and resistance training studies typically reported no significant changes in time to 5 m or 15 m, or any block phase kinetic or kinematic characteristics (24, 84, 144). The only exception to this was the significant improvements in time to 5 m and 15 m observed for the subset of under 17 year old swimmers who performed maximal strength training, with no such effects reported for the under 17 year old plyometric group (144).

A possible explanation for the uncertainty regarding whether jump/plyometric or more general resistance training programs produces greater improvements in swim start performance may reflect the potential direction-specific nature of resistance training. In a review by Randell et al. (55) on the specificity of resistance training to sports performance, it was proposed training adaptations may be direction-specific, and that athletes who are required to apply forces in the horizontal plane should perform several exercises containing a horizontal component. More recently, this potential directional specificity of training has been referred to as the force-vector theory (147), with the hip thrust and prowler push/heavy sled pull being two of the most commonly used horizontal-force exercises (147-150). In support of the force-vector theory, a study by Contreras et al. (148) using the hip thrust significantly improved 10 m and 20 m sprint running times (-1.05 % and -1.67 %, respectively) compared to the front squat, which is a vertical-force exercise (+0.10 % and -0.66 %, respectively). The prowler push, which requires the athlete to push a loaded sled in the horizontal plane, has been shown to closely mimic the horizontal plane power requirements of sprinting (151). In contrast, a study involving 30 sub-elite rugby players did not support the force-vector theory as no significant between-group effects were observed between the horizontal-force oriented and traditional resistance training programs (150).

The potential direction specificity of resistance training exercises for improving aspects of swim start performance has been examined in two jump and plyometric training studies (19, 56) and two acute training studies utilising post-activation potentiation (PAP) (81, 82). Rebutini et al. (19) and Rejman et al. (56) observed a 10.4 % and 13.8 % increase in take-off velocity in the swim start post nine- and six-weeks of plyometric training, respectively that included a variety of horizontal jumps. Acute improvements in time to 5 m (81, 82) and 15 m (82) after performing PAP protocols that were biomechanically similar to the foot position in the kick start on the OSB11 start block have also been observed. However, out of these four plyometric and PAP studies, only one (82) utilised the OSB11 start block and the kick start technique currently used by high performance swimmers. More research is required to determine whether horizontal or vertical-oriented plyometric and/or PAP training can produce significant chronic improvements in 5 m and 15 m start time in high performance swimmers using the OSB11 start block.

Therefore, the primary aim of this pilot study was to gain some preliminary insight into the comparative effects of a horizontal- versus vertical-force resistance training program on swim start performance and squat jump (SJ) force-time characteristics. A secondary aim of the study was to better understand how changes in certain SJ force-time characteristics may be correlated with the changes in swim start performance in competitive swimmers.

6.4 MATERIALS AND METHODS

6.4.1 EXPERIMENTAL DESIGN

An eight-week training program sought to examine how a horizontal-force (HF) compared to vertical-force (VF) oriented emphasis resistance training program would potentially alter swim start performance. Participants were randomly assigned to either a HF or VF training group (HF: $n = 6$, VF: $n = 7$), with each group performing two resistance training sessions per week.

6.4.2 PARTICIPANTS

Thirteen participants (8 males (age 21.0 ± 1.6 years, body mass 78.6 ± 8.3 kg, height 1.80 ± 0.06 m), and 5 females (age 21.4 ± 2.0 years, body mass 67.5 ± 7.4 kg, height 1.69 ± 0.05 m)) volunteered to participate in this study. Participants were national level swimmers with at least four years' experience in competing in national championships and at least one year of land-based resistance training experience that included the barbell back squat and hip thrust under the supervision of a strength and conditioning coach. Participants with any known contraindication to maximal training performance and/or injuries that would interfere with their ability to complete the study or compromise their health and wellness were excluded. Prior to participating in this study, participants were briefed on the experimental design and gave written informed consent to participate in the study. This investigation was conducted in accordance with the Declaration of Helsinki and approved by Bond University Human Research Ethics Committee (00088).

Assessments were conducted at baseline (week one) and the end of the training program (week nine). Participants were instructed to maintain their nutritional and sleep habits, and to avoid alcohol and caffeine consumption for at least 24 hours before testing sessions. All tests were performed on the same day of the week between 7:00 am and 11:00 am, with participants having at least 12 hours of rest between their prior training session and the squat jump and swim start performance tests. Each testing session typically lasted for 1 – 2 hours. Participants first reported to the gymnasium to perform the squat jump test and then had a 30-minutes rest prior to the swim start performance test.

6.4.3 TRAINING INTERVENTION

The training program was organised into two phases. In the first phase (weeks one to four), each group performed three HF and VF lower body exercises, respectively. A direction specific lower body jump was added in the second phase for each group (weeks five to eight) (Table 6-1). The HF training group was prescribed a "start jump", which is a jump for horizontal distance initiated from a mimicked swim start position (Figure 6-1) to a two-foot landing, while the VF training group performed the squat jump. When performing the jumps, the HF group were instructed to jump as far forward as possible, while the VF group were instructed to jump as high as possible with each jump.

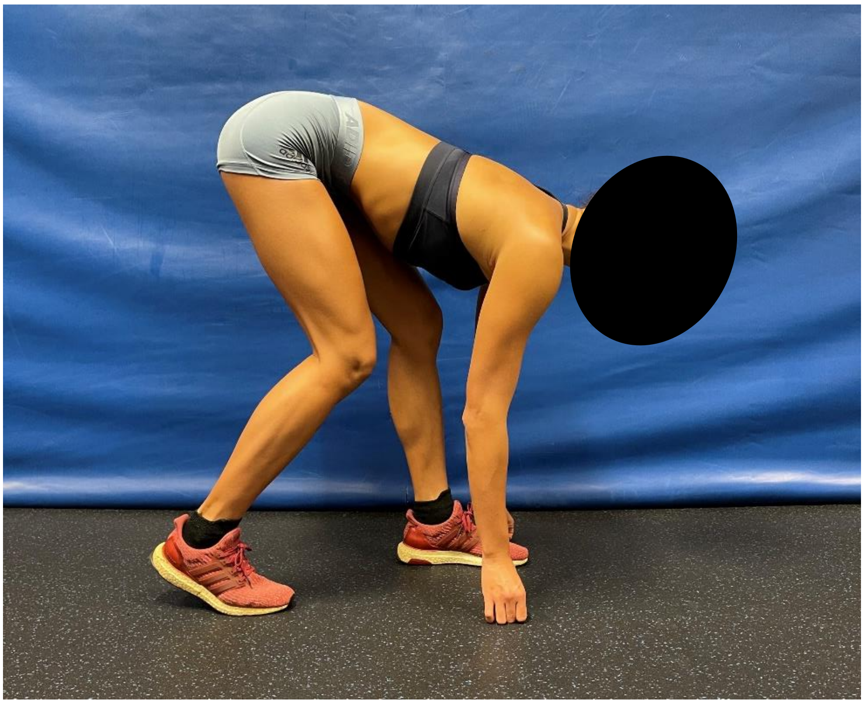

Figure 6-1. Initial positioning of the "start" jump for the Horizontal-Force (HF) training group. Photograph by the author.

Participants performed the training program utilising sets and repetition ranges typically used for developing maximal strength (152). Participants followed two 4-week mesocycle using a 3:1 loading paradigm, with a progressive increase in load for the first three weeks followed by a reduction in load in the fourth week (153). This was considered important as the swimmers were still maintaining high volumes of swimming training throughout the intervention. As the majority of propulsive forces in the free swim phase comes from the upper body (3), both groups also performed three sets of several upper body exercises including pull-ups, bench pull or seated row; and three sets of exercises for the abdominals/ lower back region, as successfully used by Contreras et al. (148) in a previous horizontal- versus vertical-force direction study. Sets were separated by a one-minute rest period (154). Training records were kept for each participant to analyse the load progression of the training program. Predicted one repetition maximum (1RM) of the hip thrust and barbell back squat was calculated pre- and post-intervention using the Brzycki equation: Predicted 1RM = weight lifted /1.0278-0.0278(no. of repetitions) (155). Repetition ranges used in the predicted 1RM was performed during the first training session (estimated from eight repetitions) and at the last training session (estimated from four repetitions). Participants were asked to refrain from performing any additional resistance training and to maintain their current diet for the course of this study.

Table 6-1. An outline of the eight-week intervention program for the Horizontal-Force (HF; n = 6) and Vertical-Force (VF; n = 5) training group with weekly sets, repetition, and load progression for the lower body strength and jumping exercises.

			Training focus							
			Strength				**Strength-power**			
			Training week							
Intervention Group	**Day**	**Exercise**	**1** Sets x reps	**2** Sets x reps	**3** Sets x reps	**4** Sets x reps	**5** Sets x reps	**6** Sets x reps	**7** Sets x reps	**8** Sets x reps
HF group	1a	Barbell hip thrust	3 x 8	3 x 8	3 x 6	2 x 6	3 x 5	3 x 5	3 x 4	2 x 4
	1b	“Start” jump					3 x 3	3 x 3	3 x 3	2 x 3
	2a	Prowler push^	3 x 8	3 x 8	3 x 6	2 x 6	3 x 5	3 x 5	3 x 4	2 x 4
	2b	Drop vertical jump					3 x 3	3 x 3	3 x 3	2 x 3
VF group	1a	Back squat	3 x 8	3 x 8	3 x 6	2 x 6	3 x 5	3 x 5	3 x 4	2 x 4
	1b	Squat jump					3 x 3	3 x 3	3 x 3	2 x 3
	2a	Rear foot elevated split squat^	3 x 8	3 x 8	3 x 6	2 x 6	3 x 5	3 x 5	3 x 4	2 x 4
	2b	Drop vertical jump					3 x 3	3 x 3	3 x 3	2 x 3

^repetitions listed are for each leg

6.4.4 SQUAT JUMP TEST

The first half hour of testing involved performance of the SJ test in the gymnasium. All participants completed a standardised dynamic warm-up consisting of a predetermined series of dynamic joint range of motion of the upper and lower body under the supervision of a strength and conditioning coach. Following the warm-up, participants were given two practice SJs before the test was conducted. All SJs were performed on a force platform (ForceDecks FD4000, London, United Kingdom), with a sample rate of 1000 Hz. Participants started in an upright standing position with their hands on their hips. They were then instructed to keep their hands on their hips to prevent the influence of arm movements for the jump trials. All participants were instructed to adopt a squat position using a self-selected depth that was held for 3 seconds before attempting to jump as high as possible (57). A successful trial was one that did not display any small amplitude countermovement at the start of the jump phase on the force trace (59). All participants performed three maximal effort SJs with a 30-second passive rest between each effort. The SJ trial with the highest jump height was kept for data analysis. Jump height was determined by the flight-time method (Jump height = $g*t^2/8$, where g is the acceleration due to gravity and t is the flight time) (156). Ground reaction force data from the SJs were analysed using the commercially available ForceDecks software (ForceDecks, London, United Kingdom). Out of the 46 variables that is provided by ForceDecks, the SJ variables that were identified by Thng et al. (136) as significant predictors of swim start performance were extracted for analysis.

6.4.5 SWIM START PERFORMANCE TEST

After a 30-minute rest, participants then performed the swim start performance test. Prior to the swim start test, all swimmers completed a pool-based warm-up based on their usual pre-race warm-up routine. Participants then performed three maximal effort swim starts to 15 m with their main swim stroke (front crawl (n = 8), butterfly (n = 3), or breaststroke (n = 2)) and preferred kick plate position, which was recorded to ensure consistency between testing sessions. Trials were started as per competition conditions and swimmers were instructed to swim to a distance past the 15 m mark, in order to ensure that representative values at the 15 m distance were obtained (115). Two-minutes of passive recovery was given between each trial (60). The start with the fastest 15 m time were selected for further analysis. Swim starts were collected using a Kistler Performance Analysis System – Swimming (KiSwim, Kistler Winterthur, Switzerland), which utilises a force instrumented starting block, constructed to match the dimensions of the Omega OSB11 block (KiSwim Type 9691A1; Kistler Winterthur, Switzerland). Time to 5 m and 15 m were collected using five calibrated high speed digital cameras operating at 100 frames per second, synchronised to the instrumented KiSwim starting block. One camera was positioned 0.95 m above the water and 2.5 m perpendicular to the direction of travel to capture the start and entry of swimmer into the water, while the other three cameras were positioned 1.3 m underwater at 5 m, 10 m and 15 m perpendicular to the swimmer to capture the time to 15 m. The times to 5 m and 15 m were defined as the time elapsed from the starting signal until the apex of the swimmers' head passed the respective distances (60). An Infinity Start System (Colorado Time Systems, Loveland, Colorado, USA) provided an audible starting signal to the athletes and an electronic start trigger to the KiSwim system. Kinetic and kinematic variables of block performance extracted for analysis were identified by Thng and colleagues as key predictors of time to 5 m and 15 m (Thng et al., unpublished data from Chapter 5). A description of the SJ and swim start variables analysed are provided in Table 6-2 (114).

Table 6-2. Description of squat jump variables obtained from the ForceDecks force platform, and the swim start variables obtained from the KiSwim Performance Analysis System.

	Variable	**Description**
ForceDecks SJ variables	Concentric impulse (N.s.)	Net impulse of vertical force during the concentric phase
	Concentric mean power (W)	Mean power during concentric phase
	Concentric rate of power development (RPD) (W/s)	Rate of power development between start of concentric phase to peak power
	Jump height (cm)	Jump height calculated from Flight Time (time between take-off and landing) in centimetres
	Reactive strength index modified (RSImod) (m/s)	Jump height (Flight Time) divided by contraction time
KiSwim swim start kinetic variables	Average acceleration (m/s/s)	Horizontal take-off velocity/ seconds from starting gun to take-off
	Average power (W/kg)	The average power relative to the swimmers' body mass produced from the starting signal to when the swimmer leaves the starting block. This was calculated as the product of (absolute force x absolute velocity) / body mass
	Horizontal take-off velocity (m/s)	The horizontal take-off velocity calculated by integrating horizontal acceleration
	Work/kg (J/kg)	Average power x seconds from the starting gun to take-off
	Front horizontal peak force (N)	Peak horizontal force on the front plate of the starting block (grab bar component not subtracted)
	Grab resultant peak force (N/BW)	Peak grab bar resultant force
	Rear horizontal peak force (N)	Peak horizontal force on the foot plate (grab bar component not subtracted)
	Total resultant peak force (N)	Peak resultant force (grab bar component subtracted)
	Rear resultant average force (N/BW)	Average resultant force on the foot plate (grab bar component not subtracted)
Swim start performance times	Time to 5 m and 15 m (s)	Time from the starting signal to a swimmers' head crossing the 5 m and 15 m mark. This is digitised at the point where the centre of the swimmers' head crosses 5 m and 15 m.

6.4.6 STATISTICAL ANALYSIS

Descriptive statistics are reported as mean ± SD for normally distributed continuous variables and frequencies for categorical variables. Normality was checked using histograms, normal Q-Q plots, and the Shapiro-Wilk test. A paired sample *t*-test was used to determine whether statistically significant differences were found between pre- and post-test means within each group. Independent *t*-tests were carried out to test for the difference in change in the outcome between intervention groups. Effect sizes (ES) with 95 % confidence intervals (95 % CI) were calculated using the Cohen's d / Hedges' g statistic as the change in mean to quantify the magnitude of differences within (i.e. post-intervention – pre-intervention results) and between the two intervention groups (i.e. HF and VF). Criteria to assess the magnitude of observed changes were: 0.0 – 0.2 trivial; 0.20 – 0.60 small; 0.60 – 1.20 moderate; and > 1.20 large (70). Effect sizes were calculated using a program created by Lenhard and Lenhard (157).

To gain some preliminary insight into how changes in the SJ force-time characteristics may be correlated with the changes in swim start performance, the association between the change scores (calculated as the difference between each individuals' pre- and post-test scores) for these outcomes were assessed by Pearson's product-moment correlation coefficient (r). Data were analysed with SPSS version 23.0.0 (SPSS Inc., Chicago, IL). P-values < 0.05 were deemed to indicate statistical significance.

6.5 RESULTS

6.5.1 TRAINING COMPLIANCE

Of the 13 initial participants, 11 participants completed the training study (Table 6-3). Two participants were removed due to: moving to another swim squad ($n = 1$) and non-adherence to the training protocol ($n = 1$). Participants completed a total of 14 ± 3 out of 16 training sessions, with the primary reasons for missed training sessions being short-term illness or domestic competitions. A summary of the within-group and between-group changes are provided in Table 6-4.

Table 6-3. Physical characteristics of participants (*N* = 11).

Variables	HF group (*n* = 6)	VF group (*n* = 5)
Age (years)	21.3 ± 1.7	21.0 ± 2.2
Sex (male / female)	3 / 3	3 / 2
Body mass (kg)	74.3 ± 10.5	70.0 ± 10.3
Height (m)	1.73 ± 0.06	1.74 ± 0.08
Weekly in-water training volume (km)	45.5 ± 17.7	53.0 ± 20.0
Weekly number of swim starts performed	9 ± 2	9 ± 2

All data, apart from the sex of the participants are presented as means and standard deviations.

6.5.2 WITHIN-GROUP CHANGES POST-INTERVENTION

Only three significant within-group differences were observed across both groups (Table 6-4). For the HF group, a significant increase in predicted 1RM hip thrust strength ($p = 0.04$) was observed. The VF group had a significant increase in KiSwim grab resultant peak force ($p = 0.007$) and a significant decrease in KiSwim resultant peak force ($p = 0.02$).

6.5.3 BETWEEN-GROUP CHANGES POST-INTERVENTION

There was a trend for the HF training group to have a greater increase in predicted 1RM strength (50 %) for the hip thrust than the increase in back squat strength for the VF training group (18 %) after 8 weeks of training. Moderate effect sizes were observed in two SJ force-time variables and five KiSwim variables (Table 6-4). Specifically, moderate effect size improvements in SJ jump height and three swim start kinetic measures were observed in the HF group. In the VF group, SJ concentric RPD and two swim start kinetic measures favoured moderate effect size improvements in the VF group.

Table 6-4. Pre- (week 1) and post- (week 9) measures of squat jump force-time variables and swim start kinetic and kinematic parameters for the horizontal-force (HF) and vertical-force (VF) training groups. Results are presented as mean ± SD except for effect sizes and change scores.

	HF group (n = 6)				**VF group (n = 5)**				**Between-group differences**	
	Week 1	**Week 9**	**Change scores**	**Within-group ES (95 % CI)**	**Week 1**	**Week 9**	**Change scores**	**Within-group ES (95 % CI)**	**Mean difference (95 % CI)**	**ES (95 % CI)**
Predicted 1RM strength										
Hip thrust (kg)	78.5 ± 15.0	118.3 ± 26.9	39.8 ± 16.6**	**1.83 (-0.08, 3.73)**						
Barbell back squat (kg)					70.6 ± 27.0	85.20 ± 38.67	14.6 ± 20.8	0.44 (-1.34, 2.21)	25.23 (-0.23, 50.70)	**1.36 (0.04, 2.67)**
SJ force-time variables										
Jump height (cm)	28.4 ± 7.5	29.1 ± 7.0	0.8 ± 3.1	0.11 (-1.50, 1.71)	29.0 ± 10.7	27.1 ± 8.3	-1.9 ± 2.9	-0.19 (-1.95, 1.56)	2.63 (-1.50, 6.76)	**0.87 (-0.37, 2.11)**
Concentric impulse (N.s.)	183.2 ± 46.2	182.3 ± 49.4	-0.9 ± 7.6	-0.02 (-1.62, 1.58)	167.3 ± 43.3	165.3 ± 44.1	-2.0 ± 8.4	-0.05 (-1.80, 1.71)	1.06 (-9.84, 11.97)	0.14 (-1.05, 1.33)
RSImod (m/s)	0.79 ± 0.16	0.73 ± 0.21	-0.07 ± 0.10	-0.32 (-1.93, 1.29)	0.75 ± 0.30	0.73 ± 0.33	-0.02 ± 0.14	-0.06 (-1.82, 1.69)	-0.04 (-0.20, 0.12)	-0.42 (-1.62, 0.78)
Concentric mean power (W)	1414.2 ± 387.6	1442.0 ± 527.8	27.8 ± 174.6	0.06 (-1.54, 1.66)	1268.0 ± 437.5	1241.0 ± 587.7	-27.0 ± 254.8	-0.05 (-1.81, 1.70)	54.8 (-238.3, 347.9)	0.26 (-0.94, 1.45)
Concentric RPD (W/s)	11986.3 ± 2879.3	10130.6 ± 3817.3	-1855.6 ± 1921.3	-0.55 (-2.18, 1.08)	10216.0 ± 5333.5	10874.5 ± 6109.3	658.4 ± 3017.4	0.12 (-1.64, 1.87)	-2514.1 (-5896.6, 868.3)	**-1.02 (-2.28, 0.24)**
KiSwim kinetic variables										
Average Power (W/kg)	19.66 ± 3.33	19.52 ± 2.94	-0.15 ± 0.63	-0.05 (-1.65, 1.56)	20.65 ± 5.42	19.91 ± 5.05	-0.74 ± 0.97	-0.14 (-1.90, 1.61)	0.59 (-0.50, 1.68)	**0.74 (-0.49, 1.97)**
Average Acceleration (m/s/s)	6.20 ± 0.80	6.15 ± 0.64	-0.04 ± 0.22	-0.07 (-1.67, 1.53)	6.42 ± 1.14	6.26 ± 1.04	-0.16 ± 0.26	-0.15 (-1.90, 1.61)	0.12 (-0.21, 0.45)	0.50 (-0.70, 1.71)
Work/kg (joules)	13.83 ± 2.00	13.91 ± 1.93	0.08 ± 0.43	0.04 (-1.56, 1.64)	13.73 ± 2.68	13.57 ± 2.51	-0.16 ± 0.39	-0.06 (-1.82, 1.69)	0.24 (-0.32, 0.80)	0.58 (-0.63, 1.79)
Horizontal take-off velocity (m/s)	4.36 ± 0.38	4.38 ± 0.36	0.03 ± 0.14	0.05 (-1.55, 1.66)	4.29 ± 0.46	4.29 ± 0.41	0.00 ± 0.09	0.00 (-1.75, 1.75)	0.03 (-0.13, 0.19)	0.25 (-0.94, -1.44)
Total resultant peak force (N/BW)	1.73 ± 0.21	1.68 ± 0.19	-0.05 ± 0.07	-0.25 (-1.86, 1.36)	1.95 ± 0.53	1.84 ± 0.55	-0.11 ± 0.06*	-0.20 (-1.96, 1.55)	-0.06 (-0.15, 0.03)	**0.91 (-0.33, 2.16)**
Front horizontal peak force (N/BW)	0.69 ± 0.07	0.70 ± 0.05	0.02 ± 0.05	0.16 (-1.44, 1.77)	0.73 ± 0.05	0.72 ± 0.09	-0.01 ± 0.05	-0.14 (-1.89, 1.62)	-0.03 (-0.09, 0.04)	**0.60 (-0.61, 1.81)**
Rear horizontal peak force (N/BW)	0.90 ± 0.19	0.88 ± 0.16	-0.02 ± 0.05	-0.11 (-1.72, 1.49)	0.91 ± 0.16	0.92 ± 0.15	0.01 ± 0.05	0.06 (-1.69, 1.82)	0.03 (-0.03, 0.10)	**-0.60 (-1.81, 0.61)**
Rear resultant average force (N/BW)	0.58 ± 0.10	0.58 ± 0.09	-0.01 ± 0.03	0.00 (-1.60, 1.60)	0.58 ± 0.13	0.57 ± 0.13	-0.01 ± 0.03	-0.08 (-1.83, 1.68)	0.00 (-0.04, 0.04)	0.00 (-1.19, 1.19)
Grab resultant peak force (N/BW)	38.67 ± 7.76	38.83 ± 7.65	0.17 ± 4.17	0.02 (-1.58, 1.62)	36.20 ± 7.92	38.80 ± 8.26	2.60 ± 1.14**	0.32 (-1.44, 2.09)	2.43 (-1.95, 6.81)	**-0.76 (-1.99, 0.47)**
Swim start performance times										
T5 m (s)	1.60 ± 0.15	1.61 ± 0.14	0.02 ± 0.03	0.07 (-1.53, 1.67)	1.59 ± 0.19	1.61 ± 0.19	0.02 ± 0.03	0.11 (-1.65, 1.86)	0.00 (-0.04, 0.04)	0.00 (-1.19, 1.19)
T15 m (s)	7.33 ± 0.69	7.32 ± 0.57	-0.01 ± 0.19	-0.02 (-1.62, 1.59)	6.82 ± 0.91	6.85 ± 0.88	0.04 ± 0.08	0.03 (-1.72, 1.79)	-0.04 (-0.28, 0.19)	-0.33 (-1.53, 0.86)

BW = bodyweight; 95 % CI = confidence interval of the differences within and between measures; ES = effect size; RPD = rate of power development SD = standard deviation; SJ = squat jump. For within group effects, a positive change score and effect size indicated that the post test score was larger than the pre-test score. For between group effects, a positive effect size indicated that the HF group had a larger change than the VF group. Bolded values indicate an effect size difference of moderate or large. $p < 0.05$*; $p < 0.01$**; $p < 0.001$*

When looking at individual changes across both groups, no significant correlations were observed between the change scores in any of the ForceDecks outcome measures and time to 5 m or 15 m. Similarly, there were no significant correlations in the change score correlations between the KiSwim outcomes and time to 15 m. However, significant correlations between the change scores for five KiSwim outcomes and time to 5 m were observed. These were average acceleration (r = -0.82, p = 0.02), horizontal take-off velocity (r = -0.81, p = 0.03), average power (r = -0.77, p = 0.05), work (r = -0.74, p = 0.01) and rear resultant average force (r = -0.71, p = 0.02).

6.6 DISCUSSION

The present pilot study was designed to provide some insight into the potential directional specificity of resistance training (now referred to as the force-vector theory) on swim start performance and squat jump (SJ) force-time characteristics in competitive swimmers. This was achieved by examining the within- and between-group training-related changes in swim start performance for two groups of competitive swimmers, who differed on whether they performed a horizontal- or vertical-force oriented emphasis resistance training program.

Relatively few significant within-group changes in any outcome measures were observed, with the non-significant changes being trivial to small in their effect sizes. The three significant within-group changes included significant increases in predicted 1RM hip thrust strength for the HF group as well as significant increases in swim start grab resultant peak force but reductions in resultant peak force for the VF group. No significant between-group differences were observed between the HF and VF groups in predicted 1RM strength, SJ force-time and swim start performance measures post-intervention. However, seven moderate between-group effect size differences were observed, with four outcome measures favouring greater improvements for the HF group and three outcome measures favouring the VF group. As such, this current study has been unable to determine whether the inclusion of horizontally oriented exercises has any clear benefit to swim start performance over more conventional vertically oriented exercises.

Possible explanations for our lack of significant within- or between-group improvements may include the small number of participants and short duration of the training intervention, inclusion of plyometric and non-plyometric jumps in only the last four of eight weeks of training, the interference effect due to concurrent training and the relative complexity of the swim start. Regarding the length of the intervention, the absence of any significant improvements in swim start performance in the current study was consistent with some studies involving 21 (144) or 23 (24) participants performing 6-8 weeks of resistance training, but inconsistent with other plyometric training studies of 6-9 weeks involving nine (56), 10 (19) or 22 (83) participants.

The potentially greater adaptations in swim start performance observed in previous plyometric studies may reflect the between study differences in plyometrics training volume. The present study only included 33 jumps, compared to previous successful plyometric studies (19, 56, 83), which included ~484 – 883 jumps across the study. Interestingly, even though Born et al. (144) included comparable volumes of plyometrics in their training study (~360 – 588 jumps) to those of the successful studies, the plyometric training group reported no significant improvements in swim start performance. While it cannot be discounted that the present study included an insufficient volume of plyometric exercise, the lack of any widespread changes in lower body force-time characteristics and swim start performance metrics observed in the present study and some of the literature (24, 144), may be indicative of the challenges coaches face in making any substantial improvements in strength and power characteristics that transfer to improved sporting performance within such short periods of concurrent training.

Concurrent training is complex in that both swim training and resistance training impose different acute stresses on the body that elicit distinct adaptations. In particular, the concurrent development of both muscular strength/power and aerobic endurance from resistance training and swimming training, respectively can lead to conflicting neuromuscular adaptations (47). In the current study, participants were primarily middle to long distance swimmers, who performed nine in-water sessions weekly (HF: 45.5 km and VF: 53 km per week). The sessions had an average swimming volume of 5.1 km and 5.8 km for the HF and VF group per session, with two swimming sessions a day performed several days per week. In contrast, the resistance training program was only performed twice per week. The interference effect from concurrent training is more likely observed with ≥ three sessions of high volume endurance training weekly (158). Therefore, the high aerobic training volume for the participants in the present study likely attenuated any resistance training-induced adaptations. Consistent with this view, Haycraft and Robertson (46) recommend swim training volumes be reduced ≤ 5 km per day to enable maximal strength and power gains and minimise neuromuscular fatigue.

It should also be acknowledged that the swim start is a discrete skill, requiring a quick reaction to the starting stimulus and the ability to effectively coordinate hand and foot forces to optimise horizontal impulse and take-off velocity. Unfortunately, the swimmers in the present study only performed a small number of swim starts per week (*n* = 9 ± 2), with this performed either during regular swim training or at the end of the session. It was also interesting to observe that Born et al. (144) also reported a low volume of swim starts (*n* = 16) performed per week. Breed, Young (24) emphasised that a higher skill component is involved in executing the swim start in comparison to vertical jump. This may reflect the requirement for how the ankle, knee, and hip joint moments needs to be coordinated effectively with those of the upper body during the block phase to maximise horizontal take-off velocity. Further, minimising the time to 15 m also requires a clean entry into the water and a streamlined glide position with undulatory leg kicks to minimise velocity loss while transitioning into the break-out of full swimming and stroking after 15 m (26). The relative absence of deliberate practice of the swim start coupled with performing the starts in a fatigued state may also help explain the minimal transfer of the resistance training interventions to improved swim start performance in the current study and that of Born et al. (144). However, significant correlations in the change scores of five block kinetic variables to time to 5 m were observed in the current study, whereby an increase in block kinetic variables was associated with a decrease in time to 5 m. Such correlations suggest that the longitudinal tracking of individual swimmers’ SJ force-time characteristics may provide some insight into their potential improvements in swim start performance.

Due to the demands of competitive swimming, it seems necessary that a targeted approach of both resistance training and deliberate practice of the swim start is required across the annual periodisation plan to improve swim start performance. This is especially important to minimise the potential adverse effects of concurrent training and maximise skill acquisition, particularly for swimmers who need to improve aspects of their swim start technique, given the complexity of the swim start. Practical recommendations include a targeted block of resistance training focused on improving the strength and power characteristics required for the swim start in a low swimming volume phase such as pre-season for a longer duration than used in the present study. Specifically, extended intervention periods > 6 months have been suggested for an optimal transfer of strength and power qualities to performance in well-trained endurance athletes (159). Incorporating greater amounts of deliberate practice of swim starts, especially at the beginning of each training session when the swimmer is mentally and physically fresh would appear to be beneficial for skill acquisition (160).

6.7 CONCLUSION

There were very few significant differences observed, either within or between the HF and VF groups after an eight-week training intervention on swim start performance. Despite exploring the inclusion of a higher proportion of horizontally oriented exercises based on the force-vector theory, the current study did not observe a transfer to improved swim start performance. However, this should not discount the potential value of including horizontally directed exercises to improve swim start performance, given the results were similar to those from more traditional vertically oriented exercises. Future studies should consider an extended training intervention completed during a phase of lower swim training volume to enable strength and power adaptions to occur.

CHAPTER 7: LONGITUDINAL TRACKING OF BODY COMPOSITION, LOWER LIMB FORCE-TIME CHARACTERISTICS AND SWIMMING START PERFORMANCE IN HIGH PERFORMANCE SWIMMERS

7.1 PREFACE

While sport scientists typically engage in extensive long-term monitoring of athletes in various sports (i.e. one year or longer), there is a relative lack of such data in peer-reviewed journals. Within the sport of swimming, these monitoring studies have typically assessed changes in swim time, as well as a variety of physiological parameters such as such as lactate and VO_2max, and biomechanical parameters such as stroke length and stroke rate. To the author's knowledge, there has been no peer-reviewed published research that has documented the long-term changes in a swimmer's body composition, strength and power characteristics, and/or swim start performance, nor how such changes may be interrelated. This chapter aims to quantify how body composition, lower body force-time, and swim start performance characteristics of high performance swimmers change over the course of a competitive season, and how these changes may be related at an intra-individual level.

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7.2 ABSTRACT

This study aimed to 1) track changes in body composition, lower body force-time characteristics, and swim start performance over a competitive season, and 2) investigate the intra-individual associations between changes in body composition and lower body force-time characteristics to swim start performance in five high performance swimmers (3 males, 2 females). Over a ~12-month period, body composition, lower body force-time characteristics and swim start performance were assessed at three time points via DXA scan, squat jump and swim start performance test, that assessed start times to 5 m and 15 m as well as several kinematic and kinetic outputs. Throughout a competitive season of concurrent swimming and dry-land resistance training, improvements in lower body lean mass and squat jump force-time characteristics were observed. However, changes in start times varied between athletes. Large negative (r = -0.57, -0.60) and positive correlations (r = 0.56) between total body lean mass for the in-water phase, as well as large to very large negative (r = -0.59, -0.66) and positive correlations (r = 0.53 to 0.73) of lower body lean mass with the flight and in-water phases were observed. Overall, these findings provide some insight into the potential magnitude of change in body composition, lower body force-time characteristics and swim start performance in high performance swimmers within a season. The large to very large correlations between increased lower body lean mass and SJ force-time metrics to improvements in aspects of start performance may provide useful information to coaches, strength and conditioning coaches, and sports scientists.

Keywords: anthropometry, long-term tracking, swim start, muscular strength, lean mass, monitoring

7.3 INTRODUCTION

High performance swimmers typically focus their annual training on peaking for one domestic national championship or qualification competition, and a subsequent major international competition (Olympic Games, World Championships, Regional Championships). Seasonal trends and individual variability in performance may occur during different time points of the season, depending on the periodisation plans and goals of the swimmer. High performance swimmers often perform several training modalities concurrently to improve their body composition, physical capacities and technical skills, with the ultimate aim to improve their competitive performance (161). As such, monitoring body composition, training and performance are commonly implemented with high performance swimmers to determine if positive adaptations have taken place in response to the training stimuli imposed (45).

Majority of the longitudinal research in the swimming literature has focused on tracking long term body composition changes and physiological variables such as blood lactate levels, biomechanical parameters such as stroke length and stroke rate, and how changes in these parameters contributes to overall swimming performance (49, 162-164). For example, seasonal and long-term improvements in body composition due to increases in lean mass and reductions in fat mass have been associated with significant improvements in swimming performance in elite and collegiate swimmers (49, 163, 165).

To the author’s knowledge, there is no longitudinal research assessing changes in swim start performance in high performance swimmers. The swim start is commonly defined as the time from the starting signal until the centre of a swimmers’ head crosses the 15 m mark and is comprised of three primary phases: block phase, flight phase and underwater phase (12), and includes an additional free swimming phase from the point of reaching the surface to the 15 m mark. The block phase requires a quick reaction to the starting signal and a take-off velocity that is primarily horizontal in direction. The block phase is followed by the flight phase, which is the projectile motion phase in which the swimmer becomes airborne and finishes when the swimmers’ head make contact with the water (14, 20). The last and the longest phase of the swim start is the underwater phase, which is defined as the period of time from when the swimmers’ head enters the water to when the swimmer begins taking their first stroke to commence free swimming (32). Total start time is calculated from the starting signal, and includes the transition between the underwater phase until a swimmer resurfaces to begin free swimming with both arms and legs, with the swimmers' head reaches 15 m (12). The ability for a swimmer to produce a quick start time to 15 m is highly dependent on an explosive muscular response, especially of the lower body musculature on the starting block to increase net impulse and maximise take-off velocity in the desired direction (19).

Recent systematic reviews (42, 108) have indicated the importance of muscular strength and power (hereafter referred to as the force-time) characteristics for enhancing the free swim and swim start phases in competitive swimming, respectively. These findings support the addition of dry-land resistance training modalities into a concurrent training model for competitive swimmers (42). However, both swim training and dry-land resistance training impose different acute stresses on the body that may elicit distinct adaptations. In particular, the concurrent development of muscular hypertrophy, strength and power from resistance training compared to the development of aerobic and anaerobic endurance from swimming training can lead to conflicting neuromuscular adaptations (47). Furthermore, the volume of swim training undertaken weekly is considerably greater than the dry-land resistance training sessions. Typically, swimmers engage in nine to ten in-water pool sessions weekly, with each session lasting one and a half to two hours. Dry-land resistance training sessions are generally performed a maximum of three times a week, totalling between three to five hours weekly (49). Thus, it can be challenging for high performance swimmers to make substantial or short-term shifts in muscular hypertrophy, strength and power compared to aerobic endurance adaptations due to the conflicting physiological adaptations associated with their concurrent training demands.

Current research on long-term tracking (one to two years) of force-time characteristics is relatively uncommon in sport science research, although some research has been performed in gymnastics, various rugby codes and American football (52-54, 166). At this stage, there appears to be no such longitudinal study within the swimming literature that have investigated the relationship between changes in body composition, force-time characteristics and/or swim start performance, and how changes in these body composition and force-time characteristics may contribute to changes in swim start performance. Therefore, the two primary aims of this study were to: 1) gain some preliminary insight into how body composition, lower body force-time characteristics, and swim start performance may change over a competitive season in five high performance swimmers; and 2) quantify the intra-individual associations between changes in body composition and lower body force-time characteristics to swim start performance. Such data will provide practitioners in high performance swimming with insight into the magnitude of change that may occur in these outcome measures across one season and how changes in different body composition and force-time characteristics may ultimately contribute to improved swim start performance.

7.4 MATERIALS AND METHODS

7.4.1 STUDY DESIGN

This longitudinal case series was carried out from November 2018 to December 2019 to quantify the time course of potential changes in body composition, lower body force-time characteristics and swim start performance in five high performance swimmers. These athletes were assessed for their body composition, lower body force-time characteristics and swim start performance at three relatively equidistant time points across this year of data collection.

The following assessments were performed within each testing occasion: 1) Dual Energy X-Ray Absorptiometry (DXA) scan, 2) squat jump (SJ) test and 3) swim start performance test. All three assessments were performed on the same day. The SJ test and swim start performance test were collected as previously described by Thng et al. (136) After completing the DXA scan, all participants refuelled and had a three-hour break before performing the SJ test. Following a 30-minute rest after the SJ test, the swim start performance test was performed.

7.4.2 PARTICIPANTS

Five swimmers (3 males: M1, M2, M3, 2 females: F1, F2) volunteered to participate in this study. Participants were primarily 100 m to 200 m swimmers, with all three male swimmers' primary stroke being the front crawl (freestyle), and the two female swimmers' main stroke was breaststroke. Prior to participating in this study, participants were briefed on the experimental design and gave written informed consent to participate in the study. The study was conducted in accordance with the Declaration of Helsinki and approved by Bond University Human Research Ethics Committee (0000016006).

7.4.3 BODY COMPOSITION ASSESSMENT

Body composition was assessed using a narrow angle fan beam DXA machine (Lunar Prodigy, GE Healthcare, Madison, WI, USA), which was calibrated prior to every scan according to the manufacturer's guidelines using a phantom. All DXA scans and analysis were performed by one Australian and New Zealand Bone Mineral Society (ANZBMS) densitometry qualified technician, using the GE enCORE 2016 software (GE Healthcare). The DXA scans were conducted at a similar time of the morning (typically within 60 minutes) at all three time points. Participants reported to the DXA scan having fasted overnight; had at least 24 hours' rest between their prior training session and the DXA scan; and with their bladders voided. Participants were instructed to present in a euhydrated state and hydration status was determined by assessing the specific gravity of the first void urine sample using a refractometer (PEN-Urine S. G., Atago, Tokyo, Japan). Upon arrival, participants underwent standing height and body mass measurements prior to the DXA scan. Stretch stature was measured as per the International Society for the Advancement of Kinanthropometry (ISAK) protocol during a maximal inhalation using a medical stadiometer (Harpenden, Hotain Limited, Crymuych, UK) to the nearest 0.1 cm. Body mass was measured using an electronic medical scale to the nearest 0.1 kg (WM202, Wedderburn, Bilinga, Australia). All participants wore minimal clothing (males: i.e., swimming trunks; females: unwired sports bra and cycling shorts) and removed all metal objects from their bodies and clothes prior to the scan. Participants were then carefully positioned in a supine position on the scanning bed using the Nana positioning protocol, which has been previously reported as the best practice protocol in athletic populations (61). Previous DXA test-retest reliability of Nana positioning protocol in our laboratory had an intraclass correlation coefficient values of 0.97 – 1.00 and standard error of measurement percentage of 0.2 – 3.3 % (62).

7.4.4 SQUAT JUMP TEST

Participants first completed a standardised full body dynamic warm-up under the supervision of a strength and conditioning coach. All SJs were performed on a force platform (ForceDecks FD4000, London, United Kingdom), with a sample rate of 1000 Hz. Following the warm-up, participants were given two practice bodyweight (BW) SJs before the test was conducted. The SJ trials were performed with a self-selected squat depth, with participants instructed to keep their hands on their hips to prevent the influence of arm movements for the jump trials. An isometric hold of 3 s preceded the concentric phase of each SJ. Each participant was given three maximal effort jumps, with a 30 s passive rest in between each effort (57). The SJ trial with the highest jump height was kept for data analysis. A successful trial was one that did not display any small amplitude countermovement at the start of the jump phase on the force trace (59). Jump height was determined by the flight-time method (Jump height = $g*t^2/8$, where g is the acceleration due to gravity and t is the flight time) (156). Ground reaction force data from the SJs were analysed using the commercially available ForceDecks software (ForceDecks, London, United Kingdom). Out of the 46 variables that are provided by ForceDecks, the SJ variables selected for analysis were based on previously documented significant predictors of swim start performance identified by Thng et al. (136).

7.4.5 SWIM START PERFORMANCE TEST

Prior to the swim start test, all swimmers completed a pool-based warm-up based on their usual pre-race warm-up routine. Participants then performed three maximal effort swim starts past the 15 m mark with their main swim stroke (front crawl (*n* = 3)), and breaststroke (*n* = 2)), in order to ensure that representative values at the 15 m distance were obtained (115). Two-minutes of passive recovery was given between each trial (60). All trials were performed in their regular swim training swimsuit and preferred kick plate position, which was recorded to ensure consistency between testing sessions. The start with the fastest 15 m start time was selected for further analysis. Swim starts were collected using a Kistler Performance Analysis System – Swimming (KiSwim, Kistler Winterthur, Switzerland), which utilises a force instrumented starting block, constructed to match the dimensions of the Omega OSB11 block (KiSwim Type 9691A1; Kistler Winterthur, Switzerland) that is currently used in competitive swimming races. Time to 5 m and 15 m were collected using five calibrated high speed digital cameras operating at 100 fps, synchronised to the instrumented KiSwim starting block. One camera was positioned 0.95 m above the water and 2.5 m perpendicular to the direction of travel to capture the start and entry of swimmer into the water, while the other three cameras were positioned 1.3 m underwater at 5 m, 10 m and 15 m perpendicular to the swimmer to capture the time to 15 m. The times to 5 m and 15 m were defined as the time elapsed from the starting signal until the apex of the swimmers' head passed the respective distances (60). An Infinity Start System (Colorado Time Systems, Loveland, Colorado, USA) provided an audible starting signal to the athletes and an electronic start trigger to the KiSwim system. Kinetic and kinematic variables of block performance extracted for analysis were identified by Thng and colleagues as key predictors of time to 5 m and 15 m (Thng et al., unpublished data from Chapter 5). Analysis of the identified parameters were broken down into the block, flight, and in-water phases of the swim start. The in-water phase comprises the underwater phase and the free swimming component till the 15 m mark. A detailed description of the parameters analysed is provided in Table 7-1.

Table 7-1. Description of variables derived from the KiSwim Performance Analysis System.

Swim start phase	Parameter	Description
Block Phase	Time on block (s)	The time it takes for a swimmer to leave the block following the starting signal.
	Average power (W/kg)	The average power relative to the swimmers' body mass produced from the starting signal to when the swimmer leaves the starting block. This was calculated as: absolute force x (absolute velocity / body mass).
	Horizontal take-off velocity (m/s)	The horizontal take-off velocity calculated by integrating horizontal acceleration.
Flight phase	Take-off angle (°)	Angle of the take-off of the centre of mass of the swimmer. This was calculated by the arctan(vertical velocity of take-off divided by the horizontal velocity at take-off).
	Flight time (s)	The time from when the swimmer leaves the starting block to the point at which the apex of the swimmers' head enters the water.
	Entry distance (m)	The horizontal distance from the starting block to head entry. This was digitised at the point where the apex of the head enters the water.
In-water phase (to 15 m)	Entry phase (s)	The difference in time between the time to 5 m and the time at which the apex of the head enters the water.
	Time to 5 m (s)	Time from the starting signal to a swimmers' head crossing the 5 m mark. This is digitised at the point where the centre of the swimmers' head crosses 5 m.
	Time of 1st kick (s)	Time from the starting signal to when the swimmer initiates and completes the first kick.
	Glide phase (s)	The difference in time to 5 m and the time of first kick.
	Propulsive phase (s)	The duration from the time of 1st kick to the head crossing 15 m. This encompasses the propulsive underwater and swimming phases.
	Time to 15 m (s)	Time from the starting signal to a swimmers' head crossing the 15 m mark. This is digitised at the point where the centre of the swimmers' head crosses 15 m.

7.4.6 STATISTICAL ANALYSIS

Descriptive statistics are presented as mean ± SD for normally distributed continuous variables and frequency (%) for categorical variables. Normality was checked using histograms, normal Q-Q plots and the Shapiro-Wilk test. Repeated measures correlations (r_{rm}) with 95 % confidence intervals (CIs) were computed to assess correlations between body composition measures, squat jump force-time and KiSwim block outcome variables across the three phases of the swim start, using the R package *"rmcorr"* (167). This approach was utilised given the dependent nature of the data measured repeatedly over time per participant. The following criteria were adopted to interpret the magnitude of correlation between the test measures: < 0.1, trivial; 0.1 – 0.3, small; 0.3 – 0.5, moderate; 0.5 – 0.7, large; 0.7 – 0.9, very large; and 0.9 – 1.0, almost perfect (168). A *p*-value of < 0.05 was considered as statistically significant. All analyses were completed with statistical software R version 3.5.3.

7.5 RESULTS

Baseline characteristics of participants and their respective FINA points for each individual' best race time for their main event in 2018 are summarised in Table 7-2. The FINA point score is centred around a base time of 1000 points using the world record of the previous year. A formula is then used to calculate the points for a swim time in comparison to the base time.

Table 7-2. Mean and standard deviation (SD) of the general characteristics of participants (*N* = 5).

Participants	**Age (years)**	**Height (m)**	**Body mass (kg)**	**FINA points**
Males (*n* = 3)	22.1 ± 3.2	1.95 ± 0.08	86.8 ± 10.0	861.7 ± 39.6
Females (*n* = 2)	19.9 ± 2.5	1.75 ± 0.04	70.0 ± 5.0	817.5 ± 44.6

7.5.1 DRY-LAND RESISTANCE TRAINING AND SWIM TRAINING VOLUME

The swimmers typically trained 11 to 12 sessions per week, which consisted of 8 to 9 (90 – 120 min) pool and 3 (60 – 75 min) dry-land resistance training sessions. A 4-week swim training volume leading into each testing occasion is presented in Figure 7-1. Participants swam an average of 40.4 km leading into T1, 47.2 km leading into T2, and 35.4 km leading into T3.

The dry-land resistance training program consistently used a progressive overload approach using a 3:1 loading paradigm, with a progressive increase in load for the first three weeks followed by a reduction in load in the fourth week (153). Each resistance training session typically consisted of multi-joint free-weight and BW exercises, machines, plyometrics and swimming-specific rehabilitation exercises. The resistance training session generally comprised of strength and power-oriented exercises for the upper and lower body, ranging from 3 to 8 repetitions per set, for a total of 8 to 12 sets per session, depending on the phases of the season. All male and female swimmers completed an individualised training program throughout the year, with progressions to exercises tailored to each athlete across each 4-week mesocycle.

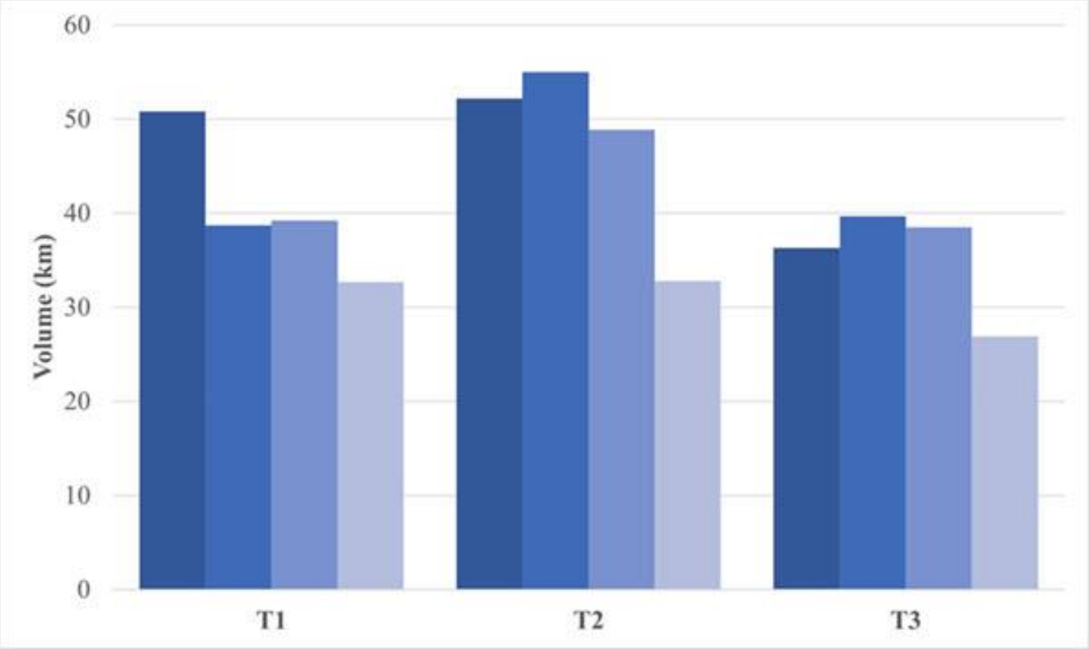

Figure 7-1. Four-week training volume across the three time points prior to each testing (T) occasion. Darker to lighter shade indicates training volumes from week T-4 to week T-1. Testing was conducted in week T-1 of each testing occasion.

7.5.2 CHANGES IN BODY COMPOSITION, SQUAT JUMP FORCE-TIME VARIABLES AND SWIM START PERFORMANCE

A summary of the changes in body composition and SJ force-time variables across the three time points for each of the five individual participants are provided in Table 7-3. While there were some inter-athlete variations, the participants typically demonstrated an increase in lower body lean mass (3.5 – 9.5 %) and jump height (3.1 – 10.3 %) over the three testing occasions. The only exception to this was F2 who demonstrated a 5.0 % increase in jump height from first to the second testing session, but a 1.1 % decrease from the second to final testing session.

Table 7-3. Body composition measures and squat jump force-time variables at each time point over 12 months.

		Body composition measures				**Squat jump force-time characteristics**		
Participant	Time point	Total body mass (kg)	Total body fat mass (kg)	Total body lean mass (kg)	Lower body lean mass (kg)	Jump height (cm)	Concentric impulse (N.s.)	RSImod (m/s)
M1	T1	96.0	16.7	76.0	22.8	37.9	261.2	1.37
	T2	96.5	15.3	77.9	24.0	39.8	273.9	1.34
	T3	95.8	17.2	75.2	24.1	40.7	273.6	1.51
M2	T1	88.3	12.9	71.6	21.4	36.0	236.6	1.03
	T2	90.1	12.4	73.9	22.4	38.2	244.5	0.98
	T3	91.7	13.3	74.5	23.2	37.1	243.5	0.92
M3	T1	76.1	13.7	59.5	16.8	38.7	203.7	1.25
	T2	77.8	13.2	61.8	17.6	37.9	197.8	1.15
	T3	79.5	13.0	63.6	18.4	42.7	229.2	1.23
F1	T1	73.5	21.4	49.5	15.4	25.3	161.8	0.59
	T2	74.8	20.9	51.3	16.3	24.4	161.9	0.54
	T3	72.8	18.5	51.7	16.8	26.4	158.8	0.60
F2	T1	66.5	19.3	44.8	14.1	27.8	155.9	0.64
	T2	65.6	17.7	45.5	14.3	29.2	158.3	0.62
	T3	67.7	19.4	45.9	14.6	27.5	160.1	0.63

T1 = November 2018; T2 = March 2019; T3 = December 2019

Table 7-4 provides a summary of the kinetic and kinematic variables of the swim start at each testing session. In contrast, to the changes in body composition and SJ force-time variables, the changes in time to 5 m and 15 m were more variable across the five swimmers. An overall increase in time to 5 m was observed in M1 and M3 (5.5 % and 2.8 % increase respectively), which contrasted with the relatively unchanged times for M2 and F2 and a 1.7 % decrease in time to 5 m for F1. With respect to time to 15 m, a 1.3 % increase was seen for M2, with M1 and F2 remaining relatively unchanged across time. Alternatively, M3 and F1 had notable improvements in time to 15 m, with a 3.1 % decrease from the first to the third testing session. Figure 7-2 illustrates the changes across the subphases of the swim start from the initial to the final testing session for each participant. Closer inspection of Figure 7-2 shows a trend for both male and female subgroups, whereby most of the changes over time were observed in the flight and underwater phases of the swim start.

Table 7-4. Swim start kinetic and kinematic variables in the block, flight, and in-water phases at each time points over 12 months.

		Block phase				**Flight phase**				**In-water phase (to 15 m)**		
Participant	Time point	Time on block (s)	Horizontal take-off velocity (m/s)	Vertical take-off velocity (m/s)	Average power (W/kg)	Take-off angle (°)	Flight time (s)	Time of entry (s)	Entry distance (m)	T1st kick (s)	T5 m (s)	T15 m (s)
M1	T1	0.76	4.87	-1.35	21.04	-15	0.24	1.00	2.86	2.13	1.45	5.97
	T2	0.74	4.58	-0.53	20.74	-7	0.32	1.06	3.08	2.48	1.46	6.03
	T3	0.79	4.56	-0.86	19.76	-11	0.31	1.10	3.09	2.37	1.53	6.00
M2	T1	0.70	4.64	-0.39	22.72	-5	0.38	1.08	3.36	1.87	1.44	6.14
	T2	0.75	4.53	-0.16	21.11	-2	0.40	1.15	3.45	2.12	1.48	6.37
	T3	0.72	4.52	-0.22	21.67	-3	0.42	1.14	3.53	1.98	1.45	6.22
M3	T1	0.65	4.58	-0.45	22.81	-6	0.35	1.00	3.06	2.01	1.44	6.41
	T2	0.67	4.49	-0.49	21.41	-6	0.33	1.00	2.92	2.14	1.48	6.36
	T3	0.68	4.53	-0.16	22.66	-2	0.37	1.05	3.22	2.20	1.48	6.21
F1	T1	0.78	4.17	-1.35	16.35	-18	0.27	1.05	2.61	3.46	1.76	8.91
	T2	0.78	4.09	-1.31	15.70	-18	0.25	1.03	2.53	3.45	1.69	8.73
	T3	0.78	4.00	-0.88	15.70	-12	0.30	1.08	2.70	3.59	1.73	8.63
F2	T1	0.74	4.33	-1.43	18.00	-18	0.24	0.98	2.61	3.14	1.67	8.66
	T2	0.74	4.17	-1.18	17.40	-16	0.28	1.02	2.69	3.63	1.64	8.49
	T3	0.77	4.19	-1.05	16.72	-14	0.28	1.05	2.80	3.43	1.68	8.68

T5 m = Time to 5 m; T15m = Time to 15 m; T1st kick = Time of first kick

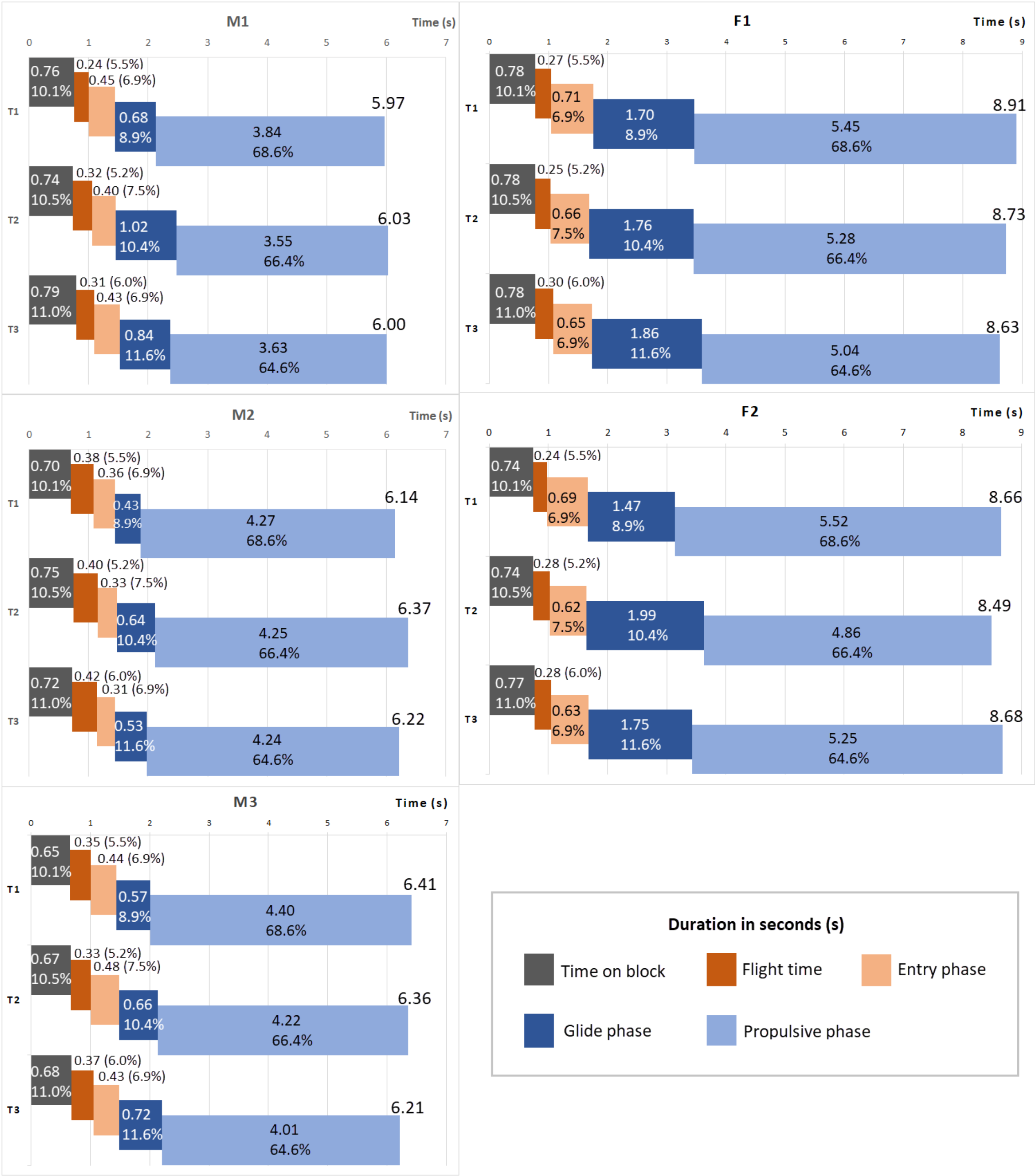

Figure 7-2. Start time to 15 m of each participant across the season in the respective phases of the swim start.

7.5.3 REPEATED MEASURES CORRELATION

The repeated measures correlations analysis was performed to gain some preliminary insight into how changes in the body composition and SJ force-time variables may be related to changes in swim start performance times (Table 7-5). Repeated measures correlations revealed moderate to large positive correlations between lower body lean mass, SJ jump height and SJ concentric impulse to the three sub-components of the flight phase. Large negative or positive correlations were observed between total body and lower body lean mass to the in-water phase to 15 m. Of all the variables monitored, total body fat mass was the only variable to show a notable correlation to the overall performance measure of start time to 15 m. Overall, these results indicate significant moderate to large correlations for a variety of body composition, squat jump, and starting block kinetic variables with the time spent in different phases of the swim start, but relatively little relationship to time to 5 m or 15 m.

Table 7-5. Repeated measures correlation (r_{rm}) scores and 95 % confidence intervals between body composition measures, squat jump force-time and swim start kinetic and kinematic variables of the swim start across the three phases of the swim start.

		Block phase	**Flight phase**			**In-water phase (to 15 m)**				
		Time on block (s)	Take-off angle (°)	Flight time (s)	Entry distance (m)	Entry phase (s)	Glide phase (s)	T5 m (s)	Propulsive phase (s)	T15 m (s)
Body composition measures	Total body mass (kg)	0.43 (-0.33, 0.85)	0.26 (-0.49, 0.79)	0.19 (-0.54, 0.76)	0.38 (-0.38, 0.83)	-0.30 (-0.80, 0.45)	0.12 (-0.59, 0.73)	0.15 (-0.57, 0.74)	-0.08 (-0.71, 0.61)	0.05 (-0.64, 0.69)
	Total body fat mass (kg)	0.21 (-0.53, 0.77)	**-0.66** (-0.92, 0.02)*	-0.43 (-0.85, 0.33)	-0.23 (-0.77, 0.52)	**0.51** (-0.23, 0.88)	**-0.67** (-0.92, -0.02)*	0.24 (-0.50, 0.78)	**0.74** (0.14, 0.94)*	**0.52** (-0.22, 0.88)
	Total body lean mass (kg)	0.23 (-0.51, 0.78)	**0.67** (0.01, 0.92)*	0.44 (-0.31, 0.86)	0.47 (-0.28, 0.86)	**-0.60** (-0.90, 0.11)	**0.56** (-0.16, 0.89)	-0.04 (-0.68, 0.64)	**-0.57** (-0.90, 0.15)	-0.30 (-0.80, 0.45)
	Lower body lean mass (kg)	0.44 (-0.32, 0.85)	**0.73** (0.14, 0.94)*	**0.70** (0.08, 0.93)*	**0.70** (0.08, 0.93)*	**-0.66** (-0.92, 0.01)*	**0.53** (-0.21, 0.88)	0.28 (-0.48, 0.80)	**-0.59** (-0.90, 0.11)	-0.30 (-0.81, 0.45)
Squat jump force-time variables	Jump height (cm)	0.40 (-0.36, 0.84)	**0.66** (-0.02, 0.92)*	**0.70** (0.06, 0.93)*	**0.76** (0.21, 0.95)**	-0.49 (-0.87, 0.25)	**0.54** (-0.20, 0.89)	0.41 (-0.35, 0.84)	**-0.62** (-0.91, 0.08)*	-0.30 (-0.80, 0.45)
	Concentric impulse (N.s.)	0.38 (-0.38, 0.83)	**0.57** (-0.15, 0.90)	**0.60** (-0.11, 0.90)	**0.78** (0.24,0.95)**	-0.49 (-0.87, 0.26)	0.39 (-0.37, 0.84)	0.30 (-0.45, 0.80)	-0.42 (-0.85, 0.33)	-0.17 (-0.75, 0.55)
	RSImod (m/s)	0.27 (-0.48, 0.79)	-0.02 (-0.67, 0.66)	0.15 (-0.60, 0.74)	0.25 (-0.50, 0.79)	0.15 (-0.57, 0.74)	-0.20 (-0.76, 0.53)	0.47 (-0.29, 0.86)	0.05 (-0.64, 0.69)	-0.07 (-0.70, 0.62)
KiSwim block outcome variables	Average power (W/kg)	**-0.73** (-0.94, -0.12)*	-0.32 (-0.81, 0.44)	-0.31 (-0.81, 0.45)	-0.21 (-0.77, 0.53)	0.28 (-0.47, 0.80)	-0.44 (-0.85, 0.32)	-0.47 (-0.86, 0.28)	0.30 (-0.46, 0.80)	-0.19 (-0.76, 0.54)
	Horizontal take-off velocity (m/s)	-0.32 (-0.81, 0.43)	**-0.76** (-0.95, -0.19)**	**-0.82** (-0.96, -0.35)**	**-0.62** (-0.91, 0.08)*	**0.66** (-0.02, 0.92)*	**-0.76** (-0.95, -0.20)**	-0.31 (-0.81, 0.44)	**0.70** (0.06, 0.93)*	0.15 (-0.57, 0.74)

T5 m = Time to 5 m; T15m = Time to 15 m; T1st kick = Time of first kick; Bolded values indicate a moderate to large r_{rm} score
*$p < 0.05$; **$p < 0.01$

7.6 DISCUSSION

To our knowledge, this is the first study to quantify how body composition, lower body force-time, and swim start performance characteristics of high performance swimmers change over the course of a competitive season, and how these changes may be related at an intra-individual level. The present case series primarily demonstrated that over the course of a competitive season of concurrent swimming and dry-land resistance training, the swimmers tended to improve their lower body lean mass and SJ jump height, although changes in start performance times to 5 m and 15 m varied between athletes. Results indicated a large correlation between total body lean mass and three out of five parameters for the in-water phase, as well as large to very large correlation of lower body lean mass with times for the flight and in-water phase. The correlational analyses also indicated large to very large relationships between SJ jump height and concentric impulse to the flight phase of the swim start.

Much of the current literature has highlighted the importance of horizontal take-off velocity in the block phase, being the on-block variable most related to time to 15 m (32, 63). An unexpected finding in the current study was that all participants experienced a decrease in horizontal take-off velocity from the first to the final testing session, although this was not associated with a reduction in start performance as might have been expected based on previous research. However, it is also worth noting that the previous research highlighting the importance of horizontal take-off velocity has been cross-sectional rather than longitudinal in nature. It was interesting to note that positive shifts in body composition and lower body force-time characteristics were instead associated with an increase in take-off angle (although the take-off angle was still negative i.e. below horizontal), leading to increased flight time and entry distance with a shorter entry phase (defined as the distance from head entry to 5 m). Positive changes in physical preparation variables were also associated with a longer glide phase and a shorter time spent in the in-water propulsive phase. A number of these changes can be explained using the laws of projectile motion, whereby the swimmers centre of mass is considered a projectile once they have left the blocks, until contact is made with the water. The horizontal displacement to the point of entry (i.e. flight distance) can be improved by increasing take-off speed, angle, relative height, or a combination of these factors (169). While the lack of association between horizontal take-off velocity and start time was surprising, greater flight distances corresponding to faster time to 15 m have previously been observed at the Sydney 2000 Olympic Games (12). A similar trend was reported in an analysis of the phases of the swim start by Ruschel et al. (33), with a significant negative correlation between flight distance and start time to 15 m (*r* = -0.482). While Ruschel et al. (33) concluded that differences in horizontal velocity at take-off primarily determined the differences in the flight distance in their cross-sectional study, the results of the present study suggested that the swimmers in the present study adapted their block phase technique in a way that favoured take-off angle rather than velocity as a mechanism to further increase their entry distance over the year.

Examination of the trends in the time spent in the different sub-phases of the swim start suggested that the largest shifts in overall start performance were due to an increase in glide time and decrease in in-water propulsive time over the monitoring period. A further investigation into the correlation between the sub-phases of the swim start to time to 15 m at an intra-individual revealed significant moderate correlation of the time spent in the propulsive phase to the overall start time (*r* = 0.66). While it is not possible to provide definitive evidence of what drove these changes, there are several potential mechanisms that could help explain these findings.

Firstly, the improvements in body composition, SJ concentric impulse and jump height is indicative of improvements in the swimmers' relative force production capability that allowed a greater entry distance, as noted previously. Entry distance is significant in swim starts as the flight phase off the blocks represents the highest velocity the swimmer is travelling anywhere in the race, and entry into the water results in a substantial reduction in that velocity due to water resistance (hydrodynamic drag) exceeding air resistance (25). As such, greater entry distance observed in the present study represents an extension of that high velocity slightly further into the race. Secondly, it is possible that upon water entry swimmers were able to minimise hydrodynamic drag via their reduction in total body mass and fat mass, thereby allowing them to hold the glide phase for a longer duration to maintain the velocity acquired in the preceding phase and initiating their first kick later in the underwater phase (170). Previous research has highlighted the importance of the underwater phase as it is the longest phase of the swim start and is when the swimmer is travelling at their fastest through the water (25, 32, 34). As the free swim velocity that occurs when a swimmer resurfaces to commence the first stroke is directly related to the final velocity of the underwater phase, ensuring minimum loss in velocity during the underwater-to-free swim transition is crucial (35). The decrease in the relative contribution of the subphase from the time of the propulsive phase to time to 15 m further supports the contention that the swimmers had a more efficient underwater phase at the end of the season. In addition to reduced hydrodynamic drag as a result of decreases in total fat mass, the improvements in both lower body lean mass and SJ lower body force-time characteristics may have also enabled the swimmers to have a more effective underwater propulsive phase through stronger undulatory kicks.

Although several elements were similar in the entire sample of swimmers, some inter-individual differences were observed from the first to the final testing session. For example, total body fat mass decreased by 0.7 – 2.9 kg in two swimmers (M3 and F1), remained unchanged for F2, but increased by 0.4 – 0.5 kg in M1 and M2. Despite a decrease in total body lean mass in M1 (-0.8 kg), an increase in lower body lean mass was observed (+1.3 kg) across time. For the other four participants, the improvements in total body lean mass over the season was largely attributed to an increase in lower body lean mass. Previous investigations have found lean mass increasing during the season (163, 165), with Pyne et al. (165) noting noticeable reductions in body fat accompanied by modest increases in total body lean mass in elite swimmers. Notable improvements in total body lean mass, and lower body lean mass, as well as lower body force-time characteristics, were observed in M3 and were associated with a substantial reduction in start time to 15 m from 6.41 s to 6.21 s from the first to the final testing session. The marked improvements in SJ jump height and concentric impulse in M3, which subsequently appears to have contributed to reductions in start time to 15 m could be explained by the greater potential for improvements in lower body force-characteristics in M3 compared to the other two males. Previous research has established a minimum concentric impulse of 200 – 230 N.s in the SJ as being required for a fast start time to 15 m, with any additional impulse production appearing to have diminishing returns for improving swim start time in male swimmers (136). The improvements in swim start performance in M3 observed may therefore be explained by the increases in their concentric impulse production over time. Specifically, M3 had an initial concentric impulse of 203.7 N.s in comparison to M1 and M2 who had baseline results of 261.2 N.s and 236.6 N.s. This suggests that M1 and M2 were already above the required threshold in concentric impulse for an optimal swim start performance. This could mean that for M1 and M2 to improve their swim start performance further, possible training focus could be on improving the technical aspect of their swim start and/or on improving their power and rate of force development rather than their strength characteristics. For female swimmers, SJ concentric impulse and other factors such as RSImod and concentric rate of power development were identified as significant predictors to time to 15 m (136). As concentric impulse and RSImod were relatively unchanged for both female swimmers, it is possible that the substantial loss of total body fat mass and a concomitant increase in lean mass, combined with changes in technical factors in the flight and underwater phase could explain much of the improvements in start performance in F1 across the season and for F2 between the first and second testing session (T1 and T2).

7.7 CONCLUSION

Overall, the findings of this study provided some preliminary insight into how swim start performance, lower body force-time characteristics, and body composition may change over a year in high performance swimmers performing concurrent swimming and resistance training. An association between increased lower body lean mass and SJ force-time metrics to improvements in aspects of swim start performance were observed, with the primary contributions of these changes being to the flight and in-water phase of the swim start. Based on these results, emphasising improvements in lower body lean mass and SJ force-time metrics and assessing these periodically in a long-term monitoring program may contribute to enhanced swim start performance in high performance swimmers. The interactions between physical and technical determinants of swim start performance highlights the need for an interdisciplinary approach to improving swim start performance in high performance swimmers. Strength and conditioning coaches and sport science practitioners should consider an individualised approach when assessing performance parameters and program design to improving swimmers' start performance. We acknowledge the inherent limitations of this study being a case study design with small sample sizes. Notwithstanding these limitations, this study offers insights into the magnitude of change in body composition, lower body force-time characteristics, and swim start performance of high performance swimmers changes throughout a competitive season and how these factors may be interrelated.

CHAPTER 8: DISCUSSION

The thesis had two major aims. 1) To identify the key lower body force-time characteristics and on-block kinematic and kinetic variables related to swim start performance and 2) To investigate how changes in these characteristics resulting from concurrent swimming and dry-land resistance training may influence swim start performance.

This chapter brings the thesis together by summarising the main findings of the systematic review and four experimental studies, linking chapters together and providing practical applications that arise from the findings. Finally, limitations of the studies in this thesis were identified and future research directions proposed.

8.1 SUMMARY OF KEY FINDINGS

The aim of the systematic review in Chapter 3 was to critically appraise the current peer-reviewed literature on 1) the acute relationship between dry-land physical performance measures and swim start performance; 2) the acute effects of dry-land resistance training on swim start performance; and 3) the chronic effects of dry-land resistance training on swim start performance. This systematic review identified 16 studies (8 cross-sectional and 8 intervention studies). Out of the eight intervention studies, four were acute interventions (79-82) and the other four were chronic intervention studies (19, 56, 83, 84) ranging from three to nine weeks in duration. The findings from the cross-sectional studies indicate that kinematic or kinetic outputs from a range of lower body strength and power exercises were highly correlated with swim start performance, with these correlations appearing greatest when utilising bodyweight (BW) vertical jumping exercises. Specifically, near perfect correlations ($r > 0.90$) with jump height were observed in BW squat jump (SJ) and countermovement jump (CMJ) to swim start performance. Acute and chronic swim start performance benefits can be achieved using a post-activation potentiation (PAP) training protocol, lower body jumps, and plyometric exercises that are primarily horizontal in direction. However, of the 16 studies included in this review, only four studies (77, 79, 82, 84) used the OSB11 starting block and the kick start technique that is currently used in competitive swimming. The findings from this systematic review informed the methodology and analysis used in three experimental studies (Chapters 4, 6, and 7) conducted in this thesis.

Chapter 4 used a cross-sectional design to develop a multiple regression model to determine what lower body force-time characteristics (using the BW SJ) were able to predict swim start performance. Considering the potential sex differences in force-time characteristics during jumping (125, 126), a secondary aim was to determine whether differences existed between males and females in jump performance predictors for swim start performance. The primary findings from Chapter 4 revealed SJ concentric impulse as a key lower body force-time characteristic related to start times to 5 m and 15 m in both sexes. Nevertheless, there were some force-time characteristics that differed in predicting swim start performance in males and females.

In male swimmers (*n* = 38), concentric impulse was identified as the sole contributing SJ force-time variable to swim start performance. Due to the quadratic nature of the relationship between concentric impulse and swim start performance for males, it appears that for a quick time to 5 m and 15 m, a minimum concentric impulse of 200 – 230 N.s is required. However, any additional impulse production above 230 N.s does not seem to be associated with a faster swim start performance for most male swimmers. Thus, for male swimmers capable of producing greater than 230 N.s of impulse in the SJ, it might be beneficial to focus on improving swim start technique and/or to further develop their explosive force-time characteristics, e.g. rate of force development, as developing a high impulse over a shorter period of time when on the block is required for further improvements in swim start times.

The results for females (*n* = 34) displayed some similarities but also some differences to those observed for males. Specifically, in female swimmers, in addition to SJ concentric impulse, there were other factors, such as SJ RSImod, mean power, and concentric RPD, that were also significant predictors of start times to 5 m and 15 m. These sex-related differences may suggest that there are somewhat differing strategies used by high performance male and female swimmers during the swim start that could be attributed to differences in maximal strength capacity, load-velocity, and neuromuscular capability (123, 124). Although lower body muscular strength was not measured in the current study, maximal strength has been shown to be a limiting factor in jumping ability and other lower body measure of explosive strength. Regardless of the mechanisms underlying the potential sex-related differences in swim start performance predictors, our results highlight the need for strength and conditioning coaches to consider variations of training programs tailored to males and females to enhance swim start performance.

In Chapter 5, start trials from as many as 152 swimmers were analysed using the KiSwim Performance Analysis System to identify which block outcome kinetic measures have the greatest relationship to 15 m start time and how lower and upper body forces are sequenced in the block phase. Results of the linear mixed modelling identified all four block kinetic measures (average power, work, average acceleration, and horizontal take-off velocity) as having very large relationships ($R^2 = 0.79 – 0.83$) to 15 m start time, with average power being the strongest predictor of time to 15 m ($R^2 = 0.83$). Average power and average acceleration exhibited a curvilinear relationship to start time to 15 m, while work and horizontal take-off velocity showed a linear relationship to time to 15 m. This quadratic relationship of average power and average acceleration to 15 m start time demonstrates that the same relative change in average power and average acceleration can result in a greater improvement in time to 15 m than work or horizontal take-off velocity. This further highlights the importance of explosive force-time characteristics (e.g. high rate of force development) for an optimal block phase in the swim start.

The exploration into the mechanistic understanding of kinetic determinants of the block phase in Chapter 5 showed the importance of the rear leg initiating force production on the kick plate during the early portion of the block phase of the swim start. During the initial stages of the block phase, sequential activation of the upper body on the grab plate is essential in keeping tension throughout the entire kinetic chain to facilitate force production. These high forces need to be maintained for as long as possible till the rear leg leaves the kick plate. The front leg’s primary propulsive role in the final period of acceleration (88 – 95 % of block time) is to maintain and increase the momentum developed from the rear leg push through until front leg toe-off.

Although the findings within the review in Chapter 3 highlighted the potential direction specificity for improving aspects of swim start performance, only one (82) out of the four plyometric and PAP studies that included horizontal oriented emphasis exercises in the training intervention utilised the OSB11 start block and the kick start technique currently used by high performance swimmers. Thus, the primary aim of Chapter 6 was to gain some preliminary insight into the comparative effects of an eight-week horizontal- (HF) versus vertical-force (VF) resistance training program on swim start performance and SJ force-time characteristics in 11 competitive swimmers. A secondary aim of Chapter 6 was to better understand how the changes in SJ force-time characteristics may be correlated with the changes in swim start performance. After 8 weeks of training, within group comparison indicated that participants improved their predicted one repetition maximum (1RM) hip thrust and back squat. The HF training group showed a greater increase in predicted 1RM strength in the hip thrust as compared to the predicted 1RM strength displayed in the back squat for the VF training group (50 % vs. 18 %). Seven moderate between-group effect size differences were observed, with four outcome measures favouring greater improvements for the HF group and three outcome measures favouring the VF group. However, no significant between-group differences were observed between the HF and VF groups in predicted 1RM strength, SJ force-time and swim start performance measures post-intervention. As such, the findings in Chapter 6 were unable to determine whether a horizontal- or vertical-force training program is more effective in enhancing swim start performance after 8 weeks of resistance training.

Some reasons for the lack of within and between group effects for improvements in SJ force-time characteristics and swim start performance described in Chapter 6 may reflect the relatively short duration of the intervention and small sample sizes in each intervention group (HF: $n = 6$, VF: $n = 5$), the large volume of concurrent training and the relative lack of any deliberate practice of the swim start. The swim start is a discrete skill that requires technical ability and coordination, combined with physical capacity to effectively coordinate hand and foot forces to optimise horizontal impulse and take-off velocity in the block phase. Further, minimising the time to 15 m also requires a clean entry into the water and a streamlined glide position with undulatory leg kicks to minimise velocity loss while transitioning into the break-out of full swimming and stroking after 15 m (26).

Deliberate practice is effortful and directed at future performance that is closely monitored, with instructions provided to the athlete with an outcome goal of an improved performance (171). According to the deliberate practice theory, proficiency and expertise in a certain domain results from the amount and type of training performed (171). There seems to be a lack of deliberate practice of swim starts in training sessions for optimal skill retention for swimmers. Through current observations, swim starts are typically practiced during regular swim training and/or at the end of a training session, with swimmers in a fatigued state. The lack of practice and performing the starts in a fatigued state may make for suboptimal long-term knowledge retention.

Nevertheless, the identification of seven moderate between-group effect size differences may warrant further investigation in larger samples and longer training durations (especially during phases of the annual periodisation plan when swimming volume is reduced) to better determine whether significant differences in swim start performance may occur as a result of these training approaches.

Based on the findings in Chapters 4 and 5 regarding the lower body force-time variables and kinetic and kinematic swim start parameters most relevant to start performance, Chapter 7 involved longitudinal monitoring of body composition, lower body force-time characteristics and swim start performance over a competitive season (three timepoints over ~12 months) in five high performance swimmers. Over the course of this period of concurrent swimming and dry-land resistance training, the swimmers tended to improve their lower body lean mass and SJ jump height, although changes in start performance times to 5 m and 15 m varied between athletes. Results of the repeated measures correlation analysis indicated a large correlation between changes in total body lean mass and three out of five parameters for the in-water phase of the swim start, as well as large to very large correlation of lower body lean mass and times for the flight and in-water phases. Large to very large relationships were also observed between lower body force-time variables (SJ jump height and concentric impulse) and the flight phase of the swim start. These results may be explained firstly, by the possibility that the swimmers adapted their block start technique in a way that favoured a small increase in take-off angle and vertical force production, thereby resulting in an increased flight time and entry distance with a shorter entry phase. In addition, examinations of the trends in the time spent in the different sub-phases of the swim start revealed that the biggest shifts in start performance occurred in the flight and in-water propulsive phase across the season. In other words, the swimmers were able to travel further from the blocks before entering the water, and were better able to retain the initial velocity produced in the block phase and carry it over into the glide and in-water propulsive phases.

Secondly, it is possible that the swimmers improved their ability to minimise hydrodynamic drag during the glide phase through improved body composition (reductions in total body mass and fat mass, and an increase in lower body lean mass). Lastly, improvements in SJ force-time metrics may explain much of the decrease in the overall time spent in the in-water propulsive phase due to an increased efficiency in the underwater phase through stronger undulatory kicks. Overall, these correlations support the view that dry-land resistance training has the potential to contribute to a better start performance through improved lower body force-time metrics and simultaneous improvements in body composition throughout the season.

This case series in Chapter 7 highlighted the interactions between physical and technical components that influence a swimmer's start performance. However, the variations between individual responses may warrant further investigation regarding how high performance swimmers may improve swim start performance over the long term. Therefore, it is paramount for swim coaches, strength and conditioning coaches and sports science practitioners to work collaboratively to monitor and constantly reassess what needs to be done to improve swim start times and consequently overall swimming performance.

8.2 PRACTICAL IMPLICATIONS

The findings within this thesis can offer some useful recommendation for strength and conditioning coaches, sports science practitioners and swim coaches.

- The systematic review of the literature (Chapter 3) demonstrated that swim start performance was near perfectly related ($r > 0.90$) to BW vertical jumping exercises (CMJ and SJ) and jump height. As the swim start is a predominantly concentric only movement, the SJ is a suitable diagnostic tool to assess lower body force-time characteristics required for the swim start.
- Strength and conditioning programs should initially look to improve concentric impulse in the BW SJ exercise, as this is the only significant predictor to start times to 5 m and 15 m in male swimmers ($R^2 = 0.66$ and 0.81, respectively), and is also the strongest predictor of swim times to 5 m and 15 m for female swimmers ($R^2 = 0.69$ and 0.84, respectively). However, for male swimmers capable of producing greater than 230 N.s of impulse, it might be beneficial for the strength and conditioning programs to focus on improving their explosive force-time characteristics such as rate of force development.
- For an optimal block performance, swimmers should set themselves on the block by creating tension throughout the entire kinetic chain in the setup. Shortly after the start signal, high forces should be produced as quickly as possible on the kick plate by the rear leg. These high rear leg forces need to be maintained

for as long as possible until the rear leg leaves the kick plate. A sequential activation of the upper body on the grab plate also facilitates the contribution of these rear leg forces in the block phase. Finally, the propulsive role of the front leg on the front plate maintains and increases the momentum developed from the rear leg.

- Average power was identified as the on-block kinetic outcome variable that has the greatest relationship to start time to 15 m ($R^2 = 0.83$). Due to the curvilinear relationship that average power has with time to 15 m, the relative benefits of continuing to improve this on-block variable may have diminishing returns on performance at higher output values. For example, for swimmers who have deficits in their lower body power-generating ability, improving this should have a substantial effect on time to 15 m. However, for highly trained swimmers who are already able to produce high levels of average power, further improvements in time to 15 m may be achieved by orienting force application more horizontally on the starting blocks and/or improving other technical aspects of the flight and in-water phases.
- The observation of individual responses across a competitive season in the case series in Chapter 7 highlights the importance of long-term monitoring and tracking of individual swimmers' swim start performance, as well as body composition and lower body force-time metrics, to provide some insight into how individual athletes are responding to their resistance training and swim training programs. Through long-term monitoring and tracking, strength and conditioning coaches and sports scientists can better understand the requirements of each individual swimmer, thereby allowing continual improvements to start performance.

8.3 LIMITATIONS

The following limitations of the studies within the thesis are acknowledged:

- The measurement of baseline strength in participants in Chapter 4 would have allowed a better understanding of whether the different force-time characteristics to predict start performance between males and females may have reflected differences in muscular strength between the sexes.

- Chapter 6 highlighted some of the obstacles practitioners may face in a high performance setting in making improvements to swim start performance in a short period. In this thesis, the difficulties that were identified included: minimal deliberate practise of the swim start in training, with starts typically performed during and/or at the end of training sessions, as well as the high levels of fatigue resulting from a large amount of swimming performed in the week. The performance of swim starts after the completion of the training sessions may not be optimal for skill acquisition due to the high level of residual fatigue from prior and current training sessions.
- Due to the logistical challenges in conducting a training intervention with elite swimmers who were preparing for the Commonwealth Games and/or World Championships, only a small number of national level swimmers (*n* = 11) were recruited for the intervention study in Chapter 6. A greater number of athletes and a longer duration of the intervention could have provided more confidence in whether a horizontal-force oriented emphasis resistance training program would provide greater enhancements in swim start performance than that of a traditional vertical-force oriented emphasis program.
- The generalisability of the results in Chapter 7 is subject to certain limitations due to the small number of participants (*n* = 5). A greater sample size would be required to ascertain if the observations made in the longitudinal case series would carry over to the broader swimming population.

While limitations are acknowledged in this body of work, the number of participants included in the cross-sectional studies for this PhD project in Chapters 4 and 5 (*n* = 72 and 152, respectively) were substantially greater than reported in previous literature (*n* = 11 – 27).

To the author’s knowledge, the direction specific training intervention study (Chapter 6) was the first study that has examined the chronic effects of a horizontal- versus vertical-force oriented emphasis resistance training program on swim start performance. Similarly, the longitudinal study (Chapter 7) was also the first study to describe how body composition, lower body force-time, and swim start performance characteristics of high performance swimmers change throughout a competitive season and how these changes in body composition and force-time characteristics may be related to changes in swim start performance.

8.4 FUTURE RESEARCH DIRECTIONS

Based on the findings and limitations of the current program of research, several recommendations can be made for future research.

- The effectiveness and practicality of PAP as a pre-competition warm-up protocol to enhance swim start performance needs to be better understood. Although the potential acute benefits of resistance training using a PAP approach were identified in three studies (80-82) in the systematic review in Chapter 3, only one study (82) used the OSB11 start block and the kick start technique that is currently used in competitive swimming. In addition, the rest periods between the conditioning activity (CA) and the explosive activity (i.e. swim start) may be too short for use as a component of pre-competition warm-ups in swimming competitions. Specifically, Cuenca-Fernández et al. (81) utilised a rest period of 6 mins and Cuenca-Fernández et al. (82) and Kilduff et al. (80) utilised a rest period of 8 mins between the CA and the swim start. Since swimmers may have to wait in marshalling up to 20 minutes after completing their pool warm-ups until they compete in their specific events, these durations between the CA and swim start of 6 – 8 minutes may be too short for use as a component of pre-competition warm-ups in competitive swimming.
- Further research should seek to understand if differences exist between swimmers of differing skill levels in SJ predictors for swim start performance. Chapters 4 presented information regarding the lower body force-time requirements for swim start performance in high performance swimmers who competed at a national and international level. Therefore, these findings may not necessarily apply to novice or developing athletes due to differences in training experience and physical maturity.
- Due to the speed differences in the in-water phases of butterfly and breaststroke, Chapters 4 and 5 only included time to 15 m analysis in the front crawl as it comprised the majority of the sample in both chapters (n = 50 and n = 101, respectively). Future research could provide additional insights to determine if:
    - 1) The lower body force-time characteristics identified in Chapter 4 are similarly able to predict start time to 15 m across different strokes.
    - 2) Neuromuscular qualities underpinning swim start performance in the front crawl differs from those of the other two strokes.

- The case series in Chapter 7 provided valuable information regarding individual progress and the interactions between the physical and technical aspects of swim start performance in a small sample of high performance swimmers over the course of ~12 months. A potential progression of this work would be to include a higher frequency of testing sessions in the annual periodisation plan to account for the different physical and physiological outcomes associated with each training cycle. This frequent monitoring may allow for a better understanding of how the swimmers are responding to the different training stimulus, given the concurrent training demands and potential for conflicting neuromuscular adaptations (47). Such knowledge may provide practitioners with a better understanding of the appropriate times to prioritise different types of training (e.g. skill acquisition and physical qualities such as strength and power) to ensure continued development of a swimmer's start performance.

8.5 CONCLUSION

In summary, the results of this thesis demonstrated that:

- A combination of physical capacity, technical ability, and coordination is required for an optimal swim start performance. This highlights the need for an interdisciplinary approach among strength and conditioning coaches, sports science practitioners, swimmers, and swim coaches to allow for continual improvements of the swim start.
- To develop an appropriate exercise prescription for improving swim start performance, strength and conditioning coaches need to understand the lower body force-time characteristics and sequencing of key on-block mechanistic variables.
- An 8-week training intervention was unable to determine whether a horizontal- or vertical-force oriented emphasis training program enhances the swim start. Therefore, a longer training intervention could be conducted during phases of the annual periodisation plan with lower swim training volumes to ascertain whether improvements in swim start times may be achieved with a horizontal- or vertical-force oriented emphasis training program.

- Periodic assessments of lower body lean mass and SJ force-time metrics in a long-term monitoring program may contribute to enhanced swim start performance in high performance swimmers. Thus, constant monitoring and assessment of a swimmer's lower body force-time characteristics and swim start performance can be used to inform the prescription of dry-land resistance training exercises for the swimmer.

This programme of work contributes to the existing knowledge of exercise assessment and prescription for high performance swimmers by providing a framework for strength and conditioning coaches and sports science practitioners, which will assist a swimmer in achieving marginal gains in swim start performance and ultimately overall swimming performance.

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CHAPTER 9: APPENDICES

APPENDIX 1: INFORMED CONSENT FORM 0000016006

BOND UNIVERSITY
FACULTY OF HEALTH SCIENCES & MEDICINE

Explanatory Statement - Participant & Parent/Guardian

10/05/2017

Project Title: Longitudinal tracking of changes in dry-land measures of physical capacities and its relationship to changes in start and turn performance in national and international level swimmers

Ethics Reference Number: 0000016006

Information for the Parent

This Participant Information Statement tells you about the research study. Knowing what is involved will help you decide if you want to let your child take part in the research. Please read this Explanatory Statement in full before making a decision and ask questions about anything that you don't understand or want to know more about. This information sheet is for you to keep.

My name is Shiqi Thng and I am a PhD student currently completing a Doctor of Philosophy at Bond University under the supervision of Associate Professor Justin Keogh and Dr Simon Pearson. I am conducting a research investigation looking at identifying the most relevant dry-land strength training exercises to swimming starts and turns and in tracking how changes in these dry-land measures may relate to changes in start and turn performance in national and international level swimmers.

What does participation involve?

The aim of this study is to determine the long-term effects of dry-land resistance training and its effects on starts and turns in competitive swimming. Results generated in this study will assist in the understanding of dry-land exercises and their contribution to competitive swimming performance, in particular in swimming starts and turns.

As part of this study, your child is invited to complete two 1-hour visits to Bond Institute of Health and Sport once every 6 weeks and a 2-hour visit to Queensland Academy of Sport no fewer than 6 weeks apart over a 12 to 18-month period for a performance analysis of dryland and on-water strength and power tests such as a submaximal squat and bench pull, squat jumps, max body weight chins, power chins and bench power pull. In addition, a body composition scan will be performed using Dual-energy X-ray absorptiometry (DXA).

The DXA scan is non-invasive and painless but it does involve exposure to a small quantity of ionising radiation. The radiation exposure for a DXA scan is 0.002 mSv. For comparison, natural background radiation to which individuals living in developed countries are exposed is estimated to be around 2.5 mSv per year. The exposure to radiation during plane travel is approximately 0.005 mSv per hour, thus a 14-hour international flight from Australia to Los Angeles would expose an individual to approximately 0.07 mSv, or 35 times the radiation from a single DXA scan. Female participants that are of childbearing age who are pregnant or suspected to be pregnant will be excluded from participating in this study.

There are slight risks associated with these strength and power assessments such as delayed onset muscle soreness and/or musculoskeletal injury. However, these assessments are commonly performed in your child's regular training program and will be closely supervised by sports science professionals; who will follow best practice guidelines to further reduce these risks. In the event of negative side effects to exercise or in the unlikely event of an injury, first aid will be administered by the primary investigator. If the injury is serious, an ambulance will be called.

Why were you chosen for this study?

For this study, we are seeking national and international level competitive swimmers aged 16 - 28, with a training experience in competitive swimming under the supervision of a swim coach registered with Swimming Australia for at least 2 years and have at least 1 year of land based resistance training experience under the supervision of a strength and conditioning coach.

As little research has been done on looking at how changes dry-land strength and power capacities relate to changes in swim start and turn performance over longer term, this study aims to identify the most relevant dry-land resistance training exercises and to determine the long-term effects of dry-land resistance training and its effects on starts and turns and inform practice for the training of competitive swimmers.

Participation and Withdrawal

Participation in this study is completely voluntary and your child may withdraw at any time without risking any negative consequences. If your child chooses to withdraw participation in this study, the information your child has provided will be immediately destroyed.

Possible benefits to participants

The majority of swimming training and swimming research has focused on the free-swimming phase that occurs after completing the block start and before the turns (e.g. from 5 - 45 m of a 50 m pool). However, performance analysis statistics indicate that the starts and turns can still play a major role in determining success in swimming events. Further, the musculature most relevant to the production of propulsive forces in the starts and turns (the lower body) is quite different to that of the free swimming portion, whereby the upper body produces the majority of propulsive forces. It is anticipated that the data collected during this study will assist us in understanding how changes in a variety of dry-land strength and power capabilities may be related to improved performance of starts and turns.

Your child's participation in this study will provide important insight into the relationship of dry-land resistance training and start and turn performance for competitive swimmers. This data will better allow coaches to be able to make informed decisions on the relative importance of a land-based strength and conditioning program to assist in an individual's on-water training program. Such improved understanding may also further contribute to improving your child's swimming performance.

Use of video recordings

Video recordings will be made for the on-water analysis, in particular during the swim start on the starting block and during the swimming turn. This will be required in order to quantify the duration of your child's swim starts and turns. These videos will only be used for analysis and for illustration in conference presentations and lectures. No other use will be made of them without your expressed permission and no one outside of the immediate research team will be allowed access to the original recordings.

Confidentiality and data storage

The conduct of this research involves the collection, access, and / or use of your identified personal information. The information collected is confidential and will not be disclosed to third parties without your consent, except to meet government, legal, or other regulatory authority requirements. Your anonymity will at all times be safeguarded. For further information, consult the National Health and Medical Research Council of Australia website https://www.nhmrc.gov.au/_files_nhmrc/publications/attachments/e39.pdf

All the data collected in this study will be treated with complete confidentiality and not made accessible to any person outside of the primary research team working on this project. Data will be stored in a secured location at Bond University for a period of 5 years in accordance with the guidelines set out by the Bond University Human Research Ethics Committee.

If your child experiences any distress from participation in this research, please contact:
Shiqi Thng
04 06 910 940
shiqi.thng@student.bond.edu.au

Should you have any complaints concerning the manner in which this research is being conducted please make contact with –
Bond University Human Research Ethics Committee,
Bond University Office of Research Services.
Bond University, Gold Coast, 4229, Australia
Tel: +61 7 5595 4194 Fax: +61 7 5595 1120 email: ethics@bond.edu.au

We thank you for taking time to assist us with this research.

Yours sincerely,

Shiqi Thng Dr Justin Keogh Dr Simon Pearson

Explanatory Statement - Participant

10/05/2017

Project Title: Longitudinal tracking of changes in dry-land measures of physical capacities and its relationship to changes in start and turn performance in national and international level swimmers

Ethics Reference Number: 0000016006

Information for the Participant

You are invited to take part in this study. Please read this Explanatory Statement in full before making a decision about whether you will take part. This information sheet is for you to keep.

My name is Shiqi Thng and I am a PhD student currently completing a Doctor of Philosophy at Bond University under the supervision of Associate Professor Justin Keogh and Dr Simon Pearson. I am conducting a research investigation looking at identifying the most relevant dry-land strength training exercises to swimming starts and turns and in tracking how changes in these dry-land measures may relate to changes in start and turn performance in national and international level swimmers.

What does participation involve?

The aim of this study is to determine the long-term effects of dry-land resistance training and its effects on starts and turns in competitive swimming. Results generated in this study will assist in the understanding of dry-land exercises and their contribution to competitive swimming performance, in particular in swimming starts and turns.

As part of this study, I invite you to complete two 1-hour visits to Bond Institute of Health and Sport once every 6 weeks and a 2-hour visit to Queensland Academy of Sport no fewer than 6 weeks apart over a 12 to 18-month period for a performance analysis of dryland and on-water strength and power tests such as a submaximal squat and bench pull, squat jumps, max body weight chins, power chins and bench power pull. In addition, a body composition scan will be performed using Dual-energy X-ray absorptiometry (DXA).

The DXA scan is non-invasive and painless but it does involve exposure to a small quantity of ionising radiation. The radiation exposure for a DXA scan is 0.002 mSv. For comparison, natural background radiation to which individuals living in developed countries are exposed is estimated to be around 2.5 mSv per year. The exposure to radiation during plane travel is approximately 0.005 mSv per hour, thus a 14-hour international flight from Australia to Los Angeles would expose an individual to approximately 0.07 mSv, or 35 times the radiation from a single DXA scan. Female participants that are of childbearing age who are pregnant or suspected to be pregnant will be excluded from participating in this study.

There are slight risks associated with these strength and power assessments such as delayed onset muscle soreness and/or musculoskeletal injury. However, these assessments are commonly performed in your regular training program and will be closely supervised by sports science professionals; who will follow best practice guidelines to further reduce these risks. In the event of negative side effects to exercise or in the unlikely event of an injury, first aid will be administered by the primary investigator. If the injury is serious, an ambulance will be called.

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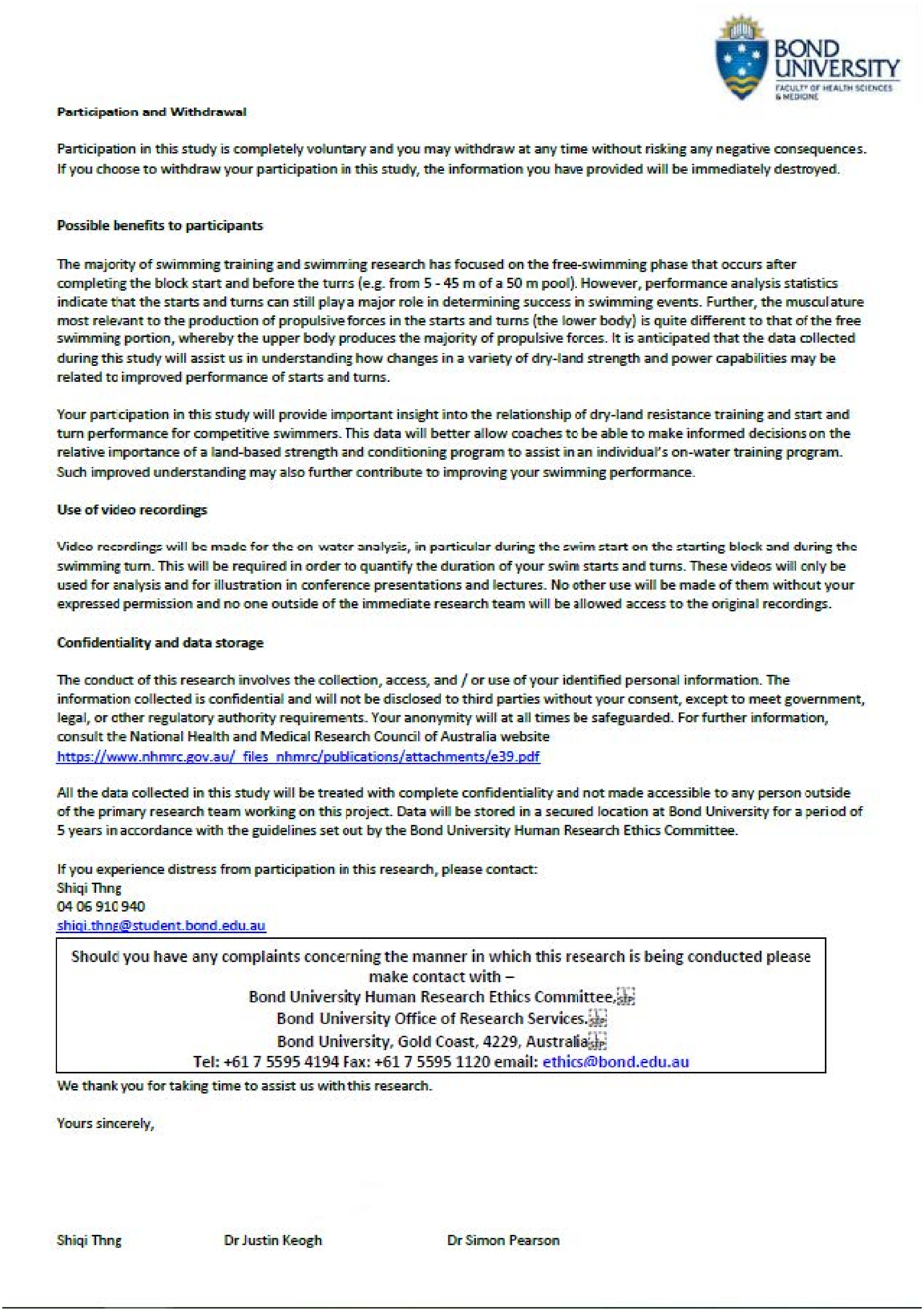
As little research has been done on looking at how changes dry-land strength and power capacities relate to changes in swim start and turn performance over longer term, this study aims to identify the most relevant dry-land resistance training exercises and to determine the long-term effects of dry-land resistance training and its effects on starts and turns and inform practice for the training of competitive swimmers.



Participation and Withdrawal

Participation in this study is completely voluntary and you may withdraw at any time without risking any negative consequences. If you choose to withdraw your participation in this study, the information you have provided will be immediately destroyed.

Possible benefits to participants

The majority of swimming training and swimming research has focused on the free-swimming phase that occurs after completing the block start and before the turns (e.g. from 5 - 45 m of a 50 m pool). However, performance analysis statistics indicate that the starts and turns can still play a major role in determining success in swimming events. Further, the musculature most relevant to the production of propulsive forces in the starts and turns (the lower body) is quite different to that of the free swimming portion, whereby the upper body produces the majority of propulsive forces. It is anticipated that the data collected during this study will assist us in understanding how changes in a variety of dry-land strength and power capabilities may be related to improved performance of starts and turns.

Your participation in this study will provide important insight into the relationship of dry-land resistance training and start and turn performance for competitive swimmers. This data will better allow coaches to be able to make informed decisions on the relative importance of a land-based strength and conditioning program to assist in an individual's on-water training program. Such improved understanding may also further contribute to improving your swimming performance.

Use of video recordings

Video recordings will be made for the on water analysis, in particular during the swim start on the starting block and during the swimming turn. This will be required in order to quantify the duration of your swim starts and turns. These videos will only be used for analysis and for illustration in conference presentations and lectures. No other use will be made of them without your expressed permission and no one outside of the immediate research team will be allowed access to the original recordings.

Confidentiality and data storage

The conduct of this research involves the collection, access, and / or use of your identified personal information. The information collected is confidential and will not be disclosed to third parties without your consent, except to meet government, legal, or other regulatory authority requirements. Your anonymity will at all times be safeguarded. For further information, consult the National Health and Medical Research Council of Australia website
https://www.nhmrc.gov.au/_files_nhmrc/publications/attachments/e39.pdf

All the data collected in this study will be treated with complete confidentiality and not made accessible to any person outside of the primary research team working on this project. Data will be stored in a secured location at Bond University for a period of 5 years in accordance with the guidelines set out by the Bond University Human Research Ethics Committee.

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We thank you for taking time to assist us with this research.

Yours sincerely,

Shiqi Thng Dr Justin Keogh Dr Simon Pearson

BOND UNIVERSITY
FACULTY OF HEALTH SCIENCES & MEDICINE

Informed Consent Form - Participant & Parent/Guardian

Project Title: Longitudinal tracking of changes in dry land measures of physical capacities and its relationship to changes in start and turn performance in national and international level swimmers

I, ………………………………………………………………………… [PRINT PARENT'S/GUARDIAN'S NAME], consent to my child ………………………………………………………………………… [PRINT CHILD'S NAME] participating in this research study.

In giving my consent I state that:

I have read the participant information sheet (document B) for the experiment and clearly understand the content, and what is being asked of my child as a participant.

The risks associated with my child's participation in the experiment have been clearly explained to me and I understand the risks involved in my child's participation in the experiment.

I have had the opportunity to ask questions about the experiment and the questions I have asked have been answered to my satisfaction. I understand I can ask questions about the experiment at any time.

I understand that personal information about my child will be handled in a confidential manner and that any reporting of my child's personal results will be de-identifiable or included together with the results of other participants.

I understand that the video recordings of my child's swim starts and turns will be handled in a confidential manner and will only be used for analysis or for illustration in conference presentations or lectures.

I understand that my child can withdraw from the experiment at any time without any negative consequences.

I understand that at the appropriate time my child will receive feedback on their performance in the experiment; to both the digital and physical addresses provided below.

I accept that my child may need to be contacted by a variety of means (email, phone, social media, etc.) for matters related to the experiment.

Shiqi Thng
Mobile: +61 0406910940
Email: shiqi.thng@student.bond.edu.au

By signing below, I clearly understand what is being asked of my child and give my consent to my child's participation in the experiment.

	PRINT Name	Signature	Date
Parent/Guardian:	________________	________________	________
Child:	____________________	________________	________

Contact Details:

Mobile: ________________________________

E-mail Address: _________________@_______________________

Postal Address: ____

____

Shiqi Thng
Mobile: +61 0406910940
Email: shiqi.thng@student.bond.edu.au

Informed Consent Form - Participant

Project Title: Longitudinal tracking of changes in dry land measures of physical capacities and its relationship to changes in start and turn performance in national and international level swimmers

I, ... [PRINT NAME], consent to participating in this research study.

In giving my consent I state that:

I have read the participant information sheet (document B) for the experiment and clearly understand the content, and what is being asked of me as a participant.

The risks associated with my participation in the experiment have been clearly explained to me and I understand the risks involved in my participation in the experiment.

I have completed the physical activity readiness questionnaire to the best of my knowledge.

I have had the opportunity to ask questions about the experiment and the questions I have asked have been answered to my satisfaction. I understand I can ask questions about the experiment at any time.

I understand that my records will be handled in a confidential manner and that any reporting of my personal results will be de-identifiable or included together with the results of other participants.

I understand that the video recordings of my swim starts and turns will be handled in a confidential manner and will only be used for analysis or for illustration in conference presentations or lectures.

I understand that I can withdraw from the experiment at any time without any negative consequences.

I understand that at the appropriate time I will receive feedback on my performance in the experiment; to both the digital and physical addresses provided below.

I accept that I may need to be contacted by a variety of means (email, phone, social media, etc.) for matters related to the experiment.

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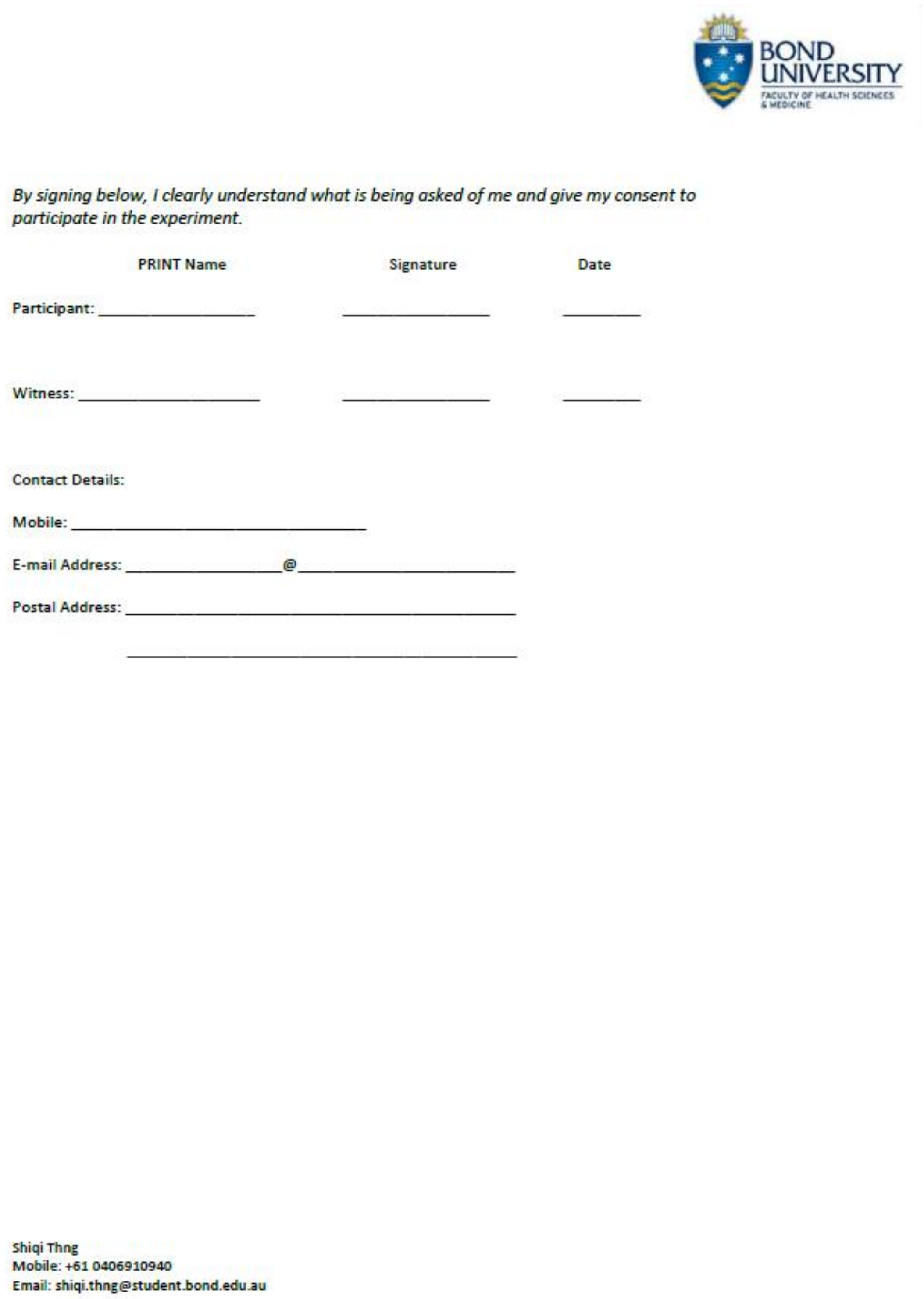

BOND UNIVERSITY
FACULTY OF HEALTH SCIENCES & MEDICINE

By signing below, I clearly understand what is being asked of me and give my consent to participate in the experiment.

	PRINT Name	Signature	Date
Participant:	________________	________________	________
Witness:	________________	________________	________

Contact Details:

Mobile: ______________________________

E-mail Address: ________________@______________________

Postal Address: ____

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APPENDIX 2: ETHICAL CLEARANCE FROM BOND UNIVERSITY IN RELATION TO THE UNIVERSITY OF QUEENSLAND HUMAN RESEARCH ETHICS COMMITTEE (HMS17/41) PROJECT

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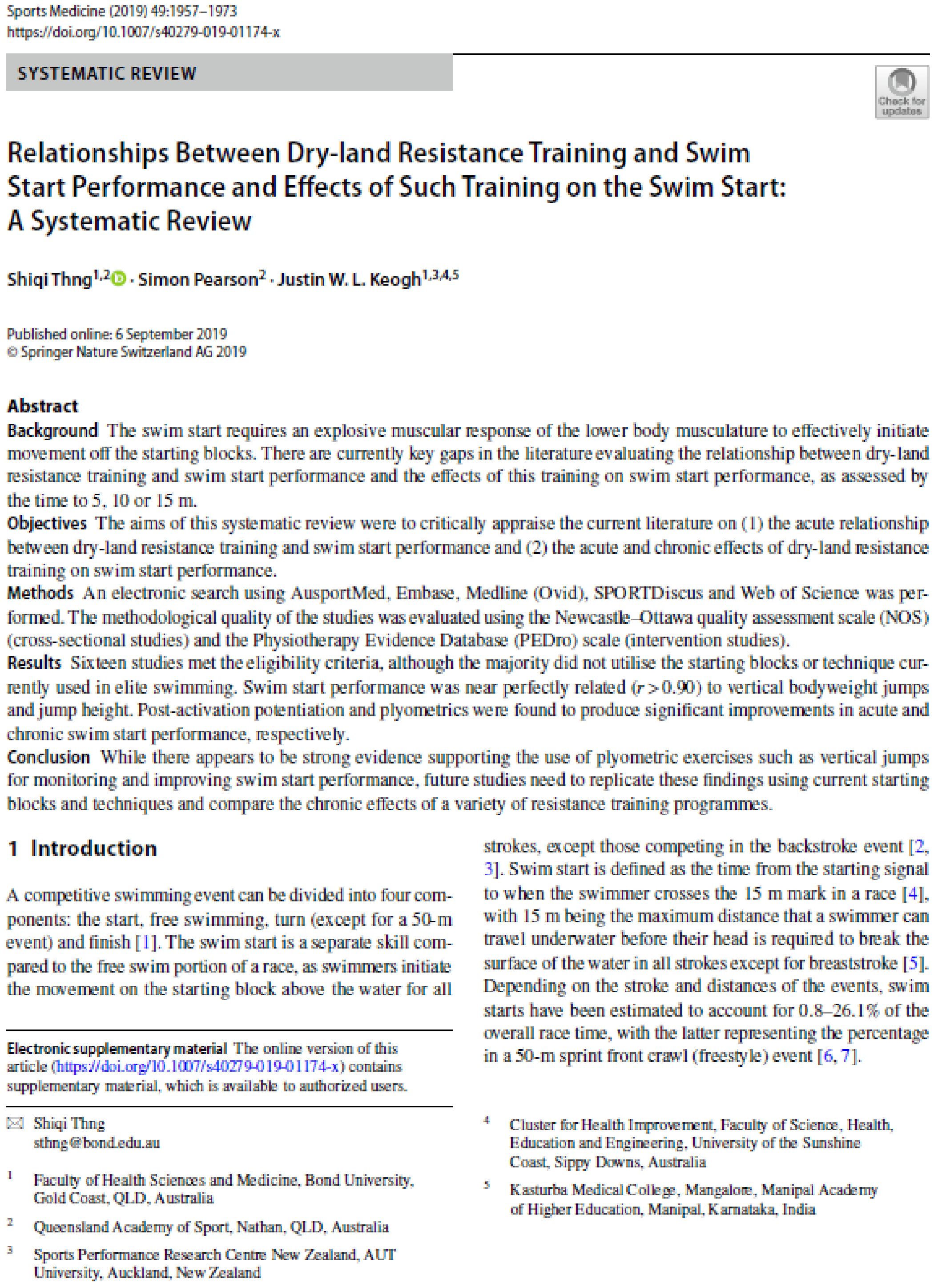
APPENDIX 5: RELATIONSHIPS BETWEEN DRY-LAND RESISTANCE TRAINING AND SWIM START PERFORMANCE AND EFFECTS OF SUCH TRAINING ON THE SWIM START: A SYSTEMATIC REVIEW – PUBLISHED VERSION



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SYSTEMATIC REVIEW

Relationships Between Dry-land Resistance Training and Swim Start Performance and Effects of Such Training on the Swim Start: A Systematic Review

Shiqi Thng[1,2] · Simon Pearson[2] · Justin W. L. Keogh[1,3,4,5]

Abstract

Background The swim start requires an explosive muscular response of the lower body musculature to effectively initiate movement off the starting blocks. There are currently key gaps in the literature evaluating the relationship between dry-land resistance training and swim start performance and the effects of this training on swim start performance, as assessed by the time to 5, 10 or 15 m.

Objectives The aims of this systematic review were to critically appraise the current literature on (1) the acute relationship between dry-land resistance training and swim start performance and (2) the acute and chronic effects of dry-land resistance training on swim start performance.

Methods An electronic search using AusportMed, Embase, Medline (Ovid), SPORTDiscus and Web of Science was performed. The methodological quality of the studies was evaluated using the Newcastle–Ottawa quality assessment scale (NOS) (cross-sectional studies) and the Physiotherapy Evidence Database (PEDro) scale (intervention studies).

Results Sixteen studies met the eligibility criteria, although the majority did not utilise the starting blocks or technique currently used in elite swimming. Swim start performance was near perfectly related ($r > 0.90$) to vertical bodyweight jumps and jump height. Post-activation potentiation and plyometrics were found to produce significant improvements in acute and chronic swim start performance, respectively.

Conclusion While there appears to be strong evidence supporting the use of plyometric exercises such as vertical jumps for monitoring and improving swim start performance, future studies need to replicate these findings using current starting blocks and techniques and compare the chronic effects of a variety of resistance training programmes.

1 Introduction

A competitive swimming event can be divided into four components: the start, free swimming, turn (except for a 50-m event) and finish [1]. The swim start is a separate skill compared to the free swim portion of a race, as swimmers initiate the movement on the starting block above the water for all strokes, except those competing in the backstroke event [2, 3]. Swim start is defined as the time from the starting signal to when the swimmer crosses the 15 m mark in a race [4], with 15 m being the maximum distance that a swimmer can travel underwater before their head is required to break the surface of the water in all strokes except for breaststroke [5]. Depending on the stroke and distances of the events, swim starts have been estimated to account for 0.8–26.1% of the overall race time, with the latter representing the percentage in a 50-m sprint front crawl (freestyle) event [6, 7].

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Key Points

Performance in a range of lower body strength and power exercises is highly correlated to swim start performance, with correlations appearing greatest when utilising bodyweight vertical jumping exercises.

Post-activation potentiation can produce significant acute improvements in swim start performance.

Plyometrics as a form of dry-land training can produce significant chronic improvements in swim start performance.

Three primary phases contribute towards the overall start time: the block phase, flight phase and underwater phase [6, 8]. A pictorial representation of the contribution of these phases and their biomechanical and anthropometric determinants is presented in Fig. 1. The block phase requires a quick reaction to the starting signal and a large take-off velocity that is primarily horizontal in direction. The block phase is followed by the flight phase, which is the projectile motion phase in which the swimmer becomes airborne and finishes when they make contact with the water [8, 9]. The underwater phase comes next, in which swimmers attempt to maintain a streamlined position through undulatory (butterfly) leg kicks with their arms outstretched in front of the head to minimise velocity loss until their head resurfaces just before the 15 m mark [2]. The average velocity in the start phase has been shown to be more than twice the velocity of the subsequent free swim phase [10, 11]. As a result, it is imperative for swimmers to maximise their velocity off the starting blocks and to maintain as much of this velocity throughout the 15-m start phase and into the remainder of the race. Key parameters from each phase that have been previously investigated as potential correlates or predictors of starting performance include time on the start block, the force the swimmer produces during the block phase, take-off velocity, angle of entry into the water, velocity at entry, time spent underwater and underwater velocity [6, 12, 13].

Biomechanical research on swim start has been conducted to identify the most effective block start technique for performance. Such research has focused on comparing a number of alternative block start techniques in an attempt to improve start performance. Prior to 2008, two styles of on-block swim start techniques were most commonly used: the grab and the track start. The primary difference between these start techniques is the foot placement on the blocks. In the grab start, both feet are positioned parallel to the front of the starting block, with the toes curled over the front edge of the starting block [14]. In the track start, one foot is placed on the front of the starting block while the other foot is placed behind [15]. The OSB11 start block (OMEGA, Zurich, Switzerland), which was introduced in 2010, features an adjustable kick plate slanted at a fixed angle of 30° that can be moved to five different positions, each at a set distance of 35 mm [8]. A kick start technique was adopted by swimmers as a result of the addition of the adjustable kick plate, where the rear foot is elevated on the angled kick plate compared to the track start technique used previously [12]. The rationale for this design was that the additional kick plate may allow for an increased duration of effective force application (i.e. greater horizontal force component) on the blocks, which in turn increases horizontal impulse and the horizontal velocity at take-off [16].

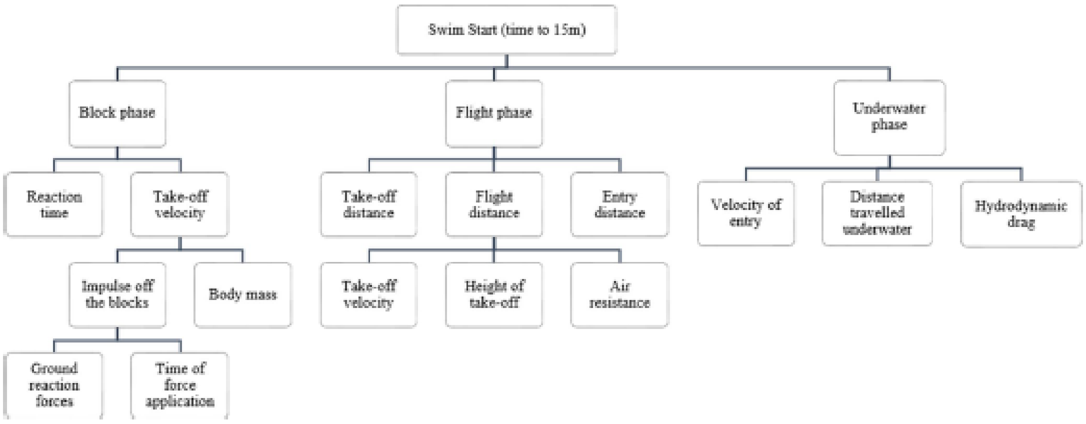

Fig. 1 Deterministic model of the swim start

The swim start requires an explosive muscular response, especially of the lower body musculature, with swimmers having to apply large forces rapidly on the start block to increase net impulse and maximise take-off velocity in the desired direction [17]. Dry-land resistance training is commonly implemented with swim training to increase lower body strength and power output. The greater the impulse (force multiplied by time of force application) produced on the start block, the greater the change in the momentum (mass multiplied by velocity) of the swimmer. Based on this relationship, the swimmer has two distinct challenges. First, is to maximise the resultant impulse while ensuring the time spent on the start block is not exceedingly long. Second, any increase in the force production capacity of the swimmer needs to be achieved with some minimisation of the hypertrophic response, as an increase in body mass will reduce the take-off velocity at a given impulse off the start block (Fig. 1).

There are key gaps in the literature evaluating the relationship between dry-land resistance training and its effects on swim start performance. A recently published systematic review examined 14 studies on resistance training in swimming, but only addressed the effects on the free swim portion of a race [18]. Gaining a clearer understanding of which kinematic and/or kinetic outputs from a variety of dry-land resistance training exercises are most related to swim start performance, as well as what dry-land resistance training programmes are most effective in improving swim start performance, may have major implications for high-performance swim programmes. Thus, the aim of this systematic review was to critically appraise the current peer-reviewed literature on (1) the acute relationship between dry-land physical performance measures and swim start performance; (2) the acute effects of dry-land resistance training on swim start performance; and (3) the chronic effects of dry-land resistance training on swim start performance.

2 Methods

2.1 Search Strategy

This systematic review followed the guidelines provided in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [19]. A comprehensive search of five electronic databases [AusportMed, Embase, Medline (Ovid), SPORTDiscus and Web of Science] was conducted on 2 August 2018. The University Faculty librarian assisted in the development of the search strategy. A combination of the following search terms were used: “swimming”, “start”, “strength”, “power” and “resistance training”. A comprehensive database search strategy is provided in the Electronic Supplementary Material Appendix S1.

2.2 Selection Criteria

After removal of duplicate studies, all study titles and abstracts were screened by two independent reviewers. Eligible articles were retrieved in full-text and evaluated for eligibility by the same two reviewers using the following criteria: (1) articles published in peer-reviewed journals and (2) journal articles with outcome measures related to the swim start. Exclusion criteria were (1) studies that were not written in English, (2) studies that were not available in full-text, (3) not an original research study, (4) a conference abstract or presentation, (5) not swimming athletes (e.g. water polo, diving, triathlon), (6) study did not measure the swim start, (7) exercises not performed on land and (8) swim start not performed on the starting block (i.e. backstroke start). The reference lists of these articles were also scanned for potentially relevant articles that were not identified in the initial database search.

2.3 Quality Assessment and Data Extraction

The quality of studies included in the review was evaluated by two independent reviewers, with differences resolved by consensus or through a third reviewer if required.

For the cross-sectional studies, the quality of studies was assessed using a modification of the Newcastle–Ottawa quality assessment scale (NOS) for cohort studies [20]. This scale has been utilised in systematic reviews of athletes [21–23] and has been recommended by the Cochrane Handbook for Systematic Reviews of Interventions for assessing methodological quality or risk of bias in non-randomised studies [24]. As follow-up for cross-sectional studies in our review was not required (item 8 on the NOS scale), we omitted that criterion in the third category and had a maximum score of 4, 2 and 2 allocated for each respective category, for a total possible score of 8. The threshold used to qualitatively assess the correlations in the cross-sectional studies was based on Hopkins [25] using the following criteria: < 0.1, trivial; 0.1–0.3, small; 0.3–0.5, moderate; 0.5–0.7, large; 0.7–0.9 very large; and > 0.9, nearly perfect.

For intervention studies, the Physiotherapy Evidence Database (PEDro) scale [26] was applied to assess the methodological quality of the literature. The PEDro scale is an 11-item scale that rates randomised controlled trials from 0 to 10, with 1 point given if the study satisfies the criteria and 0 points if not. Studies scoring 9–10 on the PEDro scale are considered methodologically excellent, 6–8 are considered good quality, 4–5 are considered fair, and those studies scoring < 4 are considered methodologically poor.

3 Results

3.1 Study Characteristics and Methodology

A total of 3369 articles were retrieved from database searches. Of the 65 studies retained for full-text screening, 16 studies were identified for review. Out of the 16 studies, eight were cross-sectional studies and eight were intervention studies. Of the intervention studies, four examined acute and four examined chronic outcomes. The results of the search process are illustrated in a flowchart shown in Fig. 2.

3.2 Cross-sectional Studies

Results from the NOS are shown in Table 1, with each study having a score between 4 and 8 of a possible 8. Table 2 summarises the number of participants, sex, age, anthropometric characteristics, dry-land and swim start tests performed and primary kinematic/kinetic swim start outcomes in each cross-sectional study. Out of the eight studies, four studies reported using the front crawl technique [4, 27–29], while the other studies did not report the swimming stroke used in the study.

Among the kinematic or kinetic outputs derived from the lower body strength/power tests, it appears that jump height and the take-off velocity obtained in the bodyweight countermovement jump (CMJ) and squat jump (SJ) had the greatest correlation with time to 5 m [28] and time to 15 m [29] out of all eight studies (Table 3). Pupisová and Pupis [30] included both grab and track starts and reported a moderate (r=0.59) and large correlation (r=0.78) of the vertical take-off velocity in the vertical jump to swim start time to 7 m and 9 m, respectively. It was unclear in the methodology of the study if any arm swing or countermovement was performed during the vertical jump.

Several studies have also examined the relationship between loaded vertical jumps and swim start performance. Peak bar velocities and jump heights from loaded SJ at four loads (25%, 50%, 75% and 100% bodyweight) had large to very large correlation with start times to 5 m, 10 m and 15 m for international female [27] and male swimmers [31]. With respect to lower body maximal and submaximal strength assessments, a very strong relationship with aspects of swim start performance was observed in the two studies that included the back squat [4, 29] (Table 3).

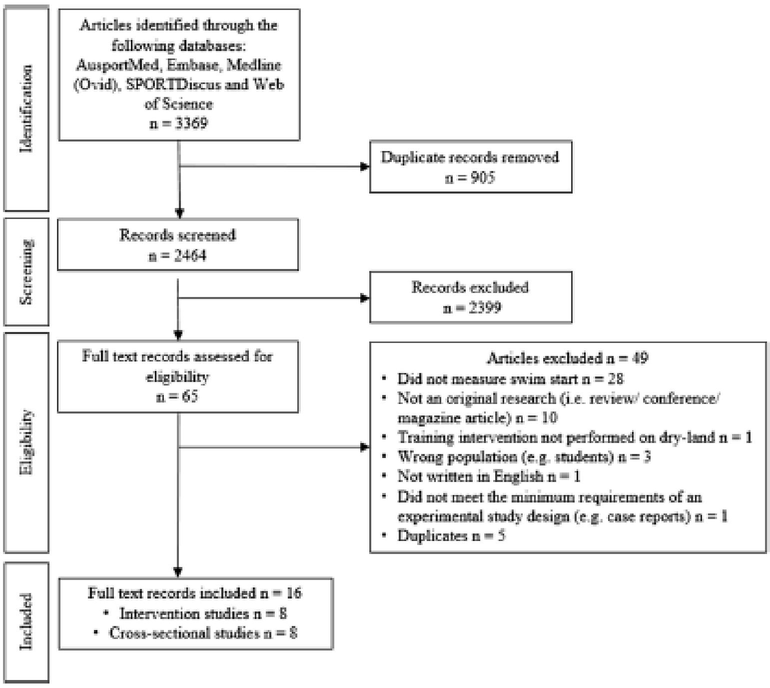

Fig. 2 Flowchart illustrating the search process according to the PRISMA guidelines. *PRISMA* Preferred Reporting Items for Systematic Reviews and Meta-Analyses

Table 1 Quality of the reviewed studies according to the Newcastle–Ottawa Scale (NOS) for cohort studies

Reference	NOS score								
	Selection				Comparability	Outcome			Total score (out of 8)
	Item 1	Item 2	Item 3	Item 4	Item 5[a]	Item 6	Item 7	Item 8	
Benjanuvatra et al. [28]	1	1	1	1	2	0	N/A	1	7
Beretic et al. [61]	1	1	1	1	2	0		1	7
Garcia-Ramos et al. [27]	1	1	1	1	2	1		1	8
Pupisová and Pupis [30]	1	1	0	0	1	0		1	4
Garcia-Ramos [31]	1	1	1	0	2	1		1	7
Đurović et al. [62]	1	1	1	1	2	0		1	7
Keiner et al. [29]	1	1	1	0	1	0		1	5
West et al. [4]	1	1	1	0	2	0		1	6
Mean									6

Notes: 0 = no; 1 = yes; item 1: representativeness of the exposed cohort; item 2: selection of the non-exposed cohort; item 3: ascertainment of exposure; item 4: demonstration that outcome of interest was not present at start of study; item 5: comparability of cohorts on the basis of the design or analysis; item 6: assessment of outcome; item 7: was follow-up long enough for outcomes to occur; item 8: adequacy of follow-up of cohorts

N/A not applicable

[a] Maximum of 2 points can be given to item 5

3.3 Intervention Studies

PEDro scores for the eight intervention studies ranged from 4 to 6 out of a maximum 11 (Table 4). Table 5 provides an overview of the acute training interventions, which includes trunk activation exercises [32] and post-activation potentiation (PAP) [33–35], while Table 6 provides an overview of the chronic training interventions, which include plyometric training [17, 36, 37] and lower body resistance training exercises [38]. Out of the eight intervention studies identified, only one study [36] utilised a controlled trial design with an intervention and control group; the remaining seven studies utilised an uncontrolled pre- and post-test design (Tables 5 and 6). The two main statistical methods used in the included intervention studies were a repeated measures analysis of variance (ANOVA) and paired *T* test.

Seven of the eight studies demonstrated that the participants showed within-group improvements in a number of kinematic and kinetic characteristics of swim start performance (Tables 5 and 6, respectively). Iizuka et al. [32] observed a 2.3% improvement in swim time to 5 m and a 5.6% improvement in the average velocity from 0 to 5 m as a result of acute trunk exercises that sought to activate deep trunk muscles such as the transverse abdominis and the internal obliques on swim start performance in nine elite level swimmers (Table 5). All three studies that investigated the acute effects of PAP on swim start performance [33–35] demonstrated significant improvements in swim start performance (Table 5).

In the four chronic intervention studies, a number of significant improvements in swim start performance were observed in all three studies involving plyometric training (Table 6). All three studies demonstrated within group improvements in take-off velocity [17, 36, 37] and horizontal take-off velocity [17]. Likewise with swim start kinematic measures, Rejman et al. [37] and Bishop et al. [36] reported a quicker swim start time to 5 m and 5.5 m (− 7.5% and − 15.2%, respectively) after the plyometric training intervention (Table 6). In contrast, Garcia-Ramos et al. [38] observed decrements in 13 international level swimmers' swim start performance (time to 10 m: + 2.3%; time to 15 m: + 3.9%, respectively) after a 3-week sea level training camp prior to an altitude training camp. Although the study's primary aim was to quantify the effects of an altitude training camp on swimming start performance, the participants performed a sea level training camp for 3 weeks prior to the altitude training camp. To allow a more direct comparison of the study by Garcia-Ramos et al. [38] with the current literature, the data presented in this section relate to their sea level training camp.

4 Discussion

The main findings from the cross-sectional studies included in this review are that swim start performance, as assessed by the time taken to reach predetermined set distances of 5, 10 and 15 m, was more highly related to (1) vertical SJ and CMJ than measures of maximal muscle strength, (2) bodyweight than loaded vertical jumps and (3) jump height than other jump kinetic or kinematic measures. The primary findings from the intervention studies included in this review

Table 2 Summary of participant background and methodology used in the included cross-sectional studies

Reference	Participants (sex)	Age (years) Anthropometrics (mean ± SD)	Dry-land exercises tested	Swim start test	Measured swim start key performance variables (units)
Grab start					
Benjanuvatra et al. [28]	9 elite and 7 recreational level swimmers (F)	Elite: 19 ± 1.3 years 1.67 ± 0.06 m 65.5 ± 10.4 kg Recreational: 22 ± 3.1 years 1.69 ± 0.07 m 57.5 ± 5.9 kg	CMJ: 6 × vertical CMJ, 6 × horizontal CMJ SJ: 6 × vertical SJ, 6 × horizontal SJ	1 × maximal effort swim to 25 m	T5 m, T10 m (s) TOV (m/s) Reaction time (s) Movement time (s) Total time spent on blocks (s) hIMP, vIMP (N/kg)
Track start					
Beretic et al. [61]	27 international level swimmers (M)	21.1 ± 4.3 years 1.89 ± 10.3 m 81.6 ± 8.4 kg	2 × 5-s leg extension MVIC at 1000 Hz	Best of 3 × swim starts to 10 m	T10 m (s)
Garcia-Ramos et al. [27]	20 international level swimmers (F)	15.3 ± 1.6 years 1.67 ± 0.06 m 57.2 ± 7.4 kg	3 × CMJ 3 × SJ 2 × loaded SJ 25, 50, 75, 100% BW each on Smith machine 2 × progressive and 2 × explosive leg extension and flexion MVIC	1 × swim start to distance slightly further than 15 m under competition rules	T5 m, T10 m, T15 m (s)
Kick start					
Garcia-Ramos [31][a]	15 national and international level swimmers (M)	17.1 ± 0.8 years 1.81 ± 0.07 m 74.1 ± 8.0 kg	2 × unloaded SJ with 0.5-kg bar Loaded SJ at 25, 50, 75, 100% BW on Smith machine	1 × swim start, using only undulatory kicks to distance slightly further than 15 m	T5 m, T10 m, T15 m (s)
Đurović et al. [62]	27 national level swimmers (M)	20.1 ± 3.4 years 1.82 ± 0.06 m 73.5 ± 7.3 kg	5 × SJ	Best of 2 × swim starts to 10 m	T10 m (s)
Keiner et al. [29]	21 regional level swimmers (12 M, 9 F)	17.5 ± 2.0 years 1.77 ± 0.10 m 69.5 ± 11.4 kg	SJ CMJ 1RM back squat 1RM deadlift	1 × maximal effort swim to 25 m under competition rules	T15 m (s)
West et al. [4]	11 international level swimmers (M)	21.3 ± 1.7 years 1.80 ± 0.10 m 78.1 ± 11.2 kg	3 × CMJ 3RM back squat	2 × swim start to distance slightly further than 15 m under competition rules	T15 m (s) hSPF (N), vSPF (N)

1RM one repetition maximum, *3RM* three repetition maximum, *BW* bodyweight, *CMJ* countermovement jump, *F* females, *hIMP* horizontal impulse, *hSPF* starting peak horizontal forces, *M* males, *MVIC* maximum voluntary isometric contraction, *SD* standard deviation, *SJ* squat jump; *T5 m* time to 5 m, *T10 m* time to 10 m, *T15 m* time to 15 m, *TOV* take-off velocity, *vIMP* vertical impulse, *vSPF* starting peak vertical forces

[a] Only sea level data were included

Table 3 Summary of the results indicating the relationship between dry-land exercises and swim start performance

Reference	Correlated dry-land exercises	Correlated dry-land key performance variables (units)	Dry-land exercise correlation to swim start performance measures				
			T5 m	T10 m	T15 m	sPFh	sPFv
Grab start							
Benjanuvatra et al. [28]	VCMJ	VCMJ-JH (cm)	$r = -0.96$**				
		VCMJ-TOV (m/s)	$r = -0.95$**				
T5 m: (recreational only)	VSJ	VSJ-JH (cm)	$r = -0.92$**				
		VSJ-TOV (m/s)	$r = -0.91$**				
T15 m: (elite only)	HCMJ	HCMJ-TOV (m/s)	$r = -0.86$*				
	HSJ	HSJ-TOV (m/s)	$r = -0.86$*				
		HSJ-JD (cm)			$r = -0.72$*		
Track start							
Beretic et al. [61]	Leg extension MVIC	F_{rel} (N/kg)		$r = -0.73$***			
		F_{max} (N)		$r = -0.56$*			
Garcia-Ramos et al. [27]	BW-CMJ	CMJ-TOV (m/s)	$r = -0.62$**	$r = -0.49$*			
	BW-CMJ	CMJ-PP_{rel} (W/kg)	$r = -0.61$**	$r = -0.55$*			
	BW-SJ	SJ-TOV (m/s)	$r = -0.56$*				
	BW-SJ	SJ-PP_{rel} (W/kg)	$r = -0.57$**				
	L-SJ at 25, 50, 75, 100% BW	BV (m/s)	BV at 50% BW $r = -0.72$**	BV at 75% BW $r = -0.59$**	BV at 75% BW $r = -0.68$**		
			BV at 25% BW $r = -0.66$**	BV at 25% BW $r = -0.57$**	BV at 100% BW $r = -0.64$**		
			BV at 75% BW $r = -0.63$**	BV at 50% BW $r = -0.57$**	BV at 25% BW $r = -0.63$**		
			BV at 100% BW $r = -0.57$*	BV at 100% BW $r = -0.50$*	BV at 50% BW $r = -0.63$**		
		PP_{rel} (W/kg)	PP_{rel} at 50% BW $r = -0.63$**	PP_{rel} at 25% BW $r = -0.55$*	PP_{rel} at 75% BW $r = -0.64$**		
			PP_{rel} at 25% BW $r = -0.62$**	PP_{rel} at 75% BW $r = -0.54$*	PP_{rel} at 100% BW $r = -0.64$**		
			PP_{rel} at 75% BW $r = -0.57$**	PP_{rel} at 50% BW $r = -0.51$*	PP_{rel} at 25% BW $r = -0.57$**		
			PP_{rel} at 100% BW $r = -0.54$*	PP_{rel} at 100% BW $r = -0.47$*	PP_{rel} at 50% BW $r = -0.54$*		
		PP (W)		PP at 25% BW $r = -0.49$*	PP at 25% BW $r = -0.49$*		
Kick start							
Garcia-Ramos [31][a]	UL-SJ with 0.5 kg bar	JH (cm)	UL-JH $r = -0.55$*	UL-JH $r = -0.77$**	JH at 75% BW $r = -0.72$**		
	L-SJ at 25, 50, 75, 100% BW		JH at 50% BW $r = -0.53$*	JH at 75% BW $r = -0.73$**	JH at 100% BW $r = -0.70$**		
			JH at 25% BW $r = -0.52$*	JH at 25% BW $r = -0.68$**	UL-JH $r = -0.67$**		
				JH at 100% BW $r = -0.68$**	JH at 25% BW $r = -0.58$*		
				JH at 50% BW $r = -0.65$**			

Table 3 (continued)

Reference	Correlated dry-land exercises	Correlated dry-land key performance variables (units)	Dry-land exercise correlation to swim start performance measures				
			T5 m	T10 m	T15 m	sPFh	sPFv
Start technique not stated							
Đurović et al. [62]	BW-SJ	PP (W)		$r = -0.39$*			
		P_{avg} (W)		$r = -0.43$*			
		F_{max} (N)		$r = -0.42$*			
		PP_{rel} (W/kg)		$r = -0.55$*			
		PP_{avgrel} (W/kg)		$r = -0.59$*			
		F_{rel} (N/kg)		$r = -0.64$**			
Keiner et al. [29]	BW-SJ	JH (cm)			$r = -0.94$*		
	BW-CMJ	JH (cm)			$r = -0.92$*		
	1RM back squat	1RM back squat (kg)			$r = -0.76$*		
	1RM deadlift	1RM deadlift (kg)			$r = -0.68$*		
West et al. [4]	BW-CMJ	PP (W)			$r = -0.85$**	$r = 0.87$**	
		JH (cm)			$r = -0.69$*	$r = 0.73$*	$r = 0.78$**
		PP_{rel} (W/kg)			$r = -0.66$*	$r = 0.78$**	$r = 0.79$**
	3RM back squat	Estimated 1RM back squat (kg)			$r = -0.74$**	$r = 0.71$*	$r = 0.62$*

Values for each study are listed from highest to lowest correlation

1RM one repetition maximum, *3RM* three repetition maximum, *BV* bar velocity, *BW* bodyweight, *CMJ* countermovement jump, F_{max} leg extensor maximum voluntary force, F_{rel} leg extensor relative maximum voluntary force, *HCMJ* horizontal countermovement jump, *HSJ* horizontal squat jump, *JD* jump distance, *JH* jump height, *L* loaded, *MVIC* maximum voluntary isometric contraction, P_{avg} average power, PP_{avgrel} average relative power, *PP* peak power, PP_{rel} relative peak power, *SJ* squat jump, *sPFh* starting peak horizontal forces, *sPFv* starting peak vertical forces, *T5 m* time to 5 m, *T10 m* time to 10 m, *T15 m* time to 15 m, *TOV* take-off velocity, *UL* unloaded, *VCMJ* vertical countermovement jump, *VSJ* vertical squat jump

$p < 0.05$; **$p < 0.01$; ***$p < 0.001$

[a]Only sea level data were included

Table 4 Quality of the included intervention studies as assessed on the Physiotherapy evidence database (PEDro) scale

Reference	PEDro scores											
	Item 1	Item 2	Item 3	Item 4	Item 5	Item 6	Item 7	Item 8	Item 9	Item 10	Item 11	Total score (out of 11)
Acute interventions												
Iizuka et al. [32]	0	0	0	0	0	0	0	1	1	1	1	4
Cuenca-Fernández et al. [35]	1	1	0	0	0	0	0	1	1	1	0	5
Cuenca-Fernández et al. [34]	1	1	0	0	0	0	0	1	1	1	1	6
Kilduff et al. [33]	1	1	0	0	0	0	0	1	1	1	0	5
Chronic interventions												
Bishop et al. [36]	1	1	0	0	0	0	0	1	1	1	0	5
Garcia-Ramos et al. [38]	0	0	0	0	0	0	0	1	1	1	1	4
Rebutini et al. [17]	1	0	0	0	0	0	0	1	1	1	0	4
Rejman et al. [37]	1	0	0	0	0	0	0	1	1	1	0	4
Mean												5

Notes: 0 = item not satisfied; 1 = item is satisfied; item 1 = eligibility criteria were specified; item 2: subjects were randomly allocated to groups; item 3: allocation was concealed; item 4: the groups were similar at baseline regarding the most important prognostic indicators; item 5: there was blinding of all subjects; item 6: there was blinding of all therapists who administered the therapy; item 7: there was blinding of all assessors who measured at least one key outcome; item 8: measures of at least one key outcome were obtained from more than 85% of the subjects initially allocated to groups; item 9: all subjects for whom outcome measures were available received the treatment or control condition as allocated or, where this was not the case, data for at least one key outcome was analysed by "intention to treat"; item 10: the results of between-group statistical comparisons are reported for at least one key outcome; item 11: the study provides both point measures and measures of variability for at least one key outcome

were (1) PAP is an effective training strategy to acutely improve swim start performance and (2) plyometrics can significantly improve swim start performance in as little as 6 weeks.

4.1 Relationship Between Dry Land Exercises and Swim Start Performance

A number of outputs from a variety of lower body exercises have been examined within the literature to determine their relationships to swim start performance. As the outputs of many of these lower body exercises exhibited nearly perfect ($r \geq 0.9$), very large ($r = 0.7$–0.9) or large ($r = 0.5$–0.7) correlations with swim start performance across a variety of levels of swimmer, the results of this systematic review confirmed the importance of lower body power and strength for optimising swim start performance. The strongest relationships with swim start performance were observed for bodyweight vertical jumping exercises (CMJ and SJ), which demonstrated nearly perfect correlations [28, 29]. Large to very large correlations were observed between the time required to complete distances of between 5 and 15 m and performance in loaded SJ at four different loads [27, 31]. Traditional strength exercises and measures of maximal muscle strength of the lower body also had a very large correlation with time to 15 m. These results suggest that a range of outputs from a variety of lower body dry-land resistance training exercises can be used to determine the lower body strength and power capacities of swimmers required for the swim start. This may reflect the requirement for high levels of force and power to be developed across the ankle, knee and hip joints and for these to be coordinated effectively with those of the upper body to maximise take-off velocity.

The different swim start techniques used in the studies identified in this systematic review may have some implications in the comparison of the results between studies. For example, even though both Benjanuvatra et al. [28] and Garcia-Ramos et al. [27] included bodyweight CMJ and SJ in their studies, there is a discrepancy between the results obtained in both studies. Benjanuvatra et al. [28] reported a nearly perfect relationship between the take-off velocity of both bodyweight CMJ and SJ with time to 5 m, whereas Garcia-Ramos et al. [27] reported a moderate to large relationship between the take-off velocity in the bodyweight CMJ with time to 10 m and 5 m, and a large relationship between the take-off velocity of the bodyweight SJ and time to 5 m. These discrepancies may be explained by the swim start technique used in each study. Benjanuvatra et al. [28] utilised the grab start, while Garcia-Ramos et al. [27] utilised the track start, with the difference between these two start techniques being the foot placement on the blocks. Pupisová and Pupis [30], who assessed swim start performance in both grab and track start conditions, reported a small correlation in the flight phase of the track start and a very large correlation in the flight phase of the grab start with the vertical jump. Unfortunately, no clear details were

Table 5 Summary of participant background, methodology and results of acute dry-land training intervention programmes on swim start performance

Reference	Participants (sex) Age (years) Anthropometrics (mean ± SD)	Dry-land training intervention protocol	Start technique	Swim test	Swim start key performance measures (units)		Results		
					Kinematics	Kinetics			
Trunk activation exercises									
Iizuka et al. [32]	9 elite level swimmers (M) 20.2 ± 1.0 years 1.74 ± 0.04 m; 68.9 ± 4.1 kg	Three trunk stabilisation exercises	Kick start	1 × swim start to 5 m			Pre	Post	
					T5 m (s)		0.83 ± 0.04	0.81 ± 0.04*	
					V5 m (m/s)		4.61 ± 0.46	4.87 ± 0.35*	
Post-activation potentiation									
Cuenca-Fernández et al. [35]^a	14 recreational swimmers (10 M, 4 F) 17 to 23 years 1.76 ± 0.09 m; 69 ± 11.4 kg	LWU: 1 × 3 each leg @ 85% 1RM YWU: 1 × 4 each leg @ MVC	Kick start	1 × maximal effort swim start to 15 m under competition rules			SWU	LWU	YWU
					T5 m (s)		1.75 ± 0.05	1.71 ± 0.05*	1.65 ± 0.04*
					T15 m (s)		7.54 ± 0.23	7.40 ± 0.21	7.36 ± 0.22*
Cuenca-Fernández et al. [34]^b	17 national level swimmers (M) 18.4 ± 1.4 years 1.81 ± 0.02 m; 73.7 ± 9.0 kg	RMWU: 1 × 3 each arm + 1 × 3 each leg @ 85% 1RM EWU: 1 × 4 each arm + 1 × 4 each leg @ MVC	Unspecified	1 × maximal effort 50 m race under competition rules			SWU	RMWU	EWU
					T5 m (s)		1.57 ± 0.11	1.52 ± 0.13*	1.52 ± 0.13*
					V5 m (m/s)		3.12 ± 0.28	3.27 ± 0.29*	3.28 ± 0.27*
					V10 m (m/s)		1.79 ± 0.17	1.83 ± 0.15*	1.84 ± 0.16*
Kilduff et al. [33]^a	9 international level sprint swimmers (7 M, 2 F) 22 ± 2 years 1.79 ± 0.14 m; 77.9 ± 11.2 kg	Barbell back squat 1 × 3 @ 87% 1RM	Unspecified	1 × swim start to 15 m under 50 m FS race conditions			Pre	Post	
						sPFv (N)	1462 ± 280	1518 ± 311*	
						sPFh (N)	770 ± 228	814 ± 263*	

1RM one repetition maximum, *EWU* arm stroke and split stance lunge on flywheel inertial device, *F* females, *FS* freestyle, *LWU* split stance lunge on Smith machine, *M* males, *MVC* maximum voluntary contraction, *RMWU* arm stroke and split stance lunge on Smith machine, *SD* standard deviation, *sPFh* starting peak horizontal forces, *sPFv* starting peak vertical forces, *SWU* standard warm-up, *T5 m* time to 5 m, *T15 m* time to 15 m, *V5 m* average velocity at 5 m, *V10 m* average velocity from 5 m to 10 m, *YWU* YoYo split stance lunge on flywheel inertial device

* $p < 0.05$

[a] 8 min' rest in between post-activation potentiation stimulus and swim start

[b] 6 min' rest in between post-activation potentiation stimulus and swim start

Table 6 Summary of participant background, methodology and results of chronic dry-land training intervention programmes on swim start performance

Reference	Participant (sex) Age (years) Anthropometrics (mean ± SD)	Dry-land training intervention protocol; intervention duration	Start technique	Swim test	Swim start key performance measures (units)		Results	
					Kinematics	Kinetics		
Plyometric exercises								
Bishop et al. [36]	22 adolescent swimmers (not stated) PT: 13.1 ±1.4 years; control: 12.6 ± 1.9 years PT: 1.63 ±0.12 m; control: 1.58 ± 0.12 m PT: 50.6 ±12.3 kg; control: 43.3 ± 11.6 kg	2× 60 min/week consisting of skips, hops and jumps for lower body; 8 weeks	Preferred technique	1 × swim start to 5.5 m			Pre	Post
					T5.5 m (s)		Control: 3.94 ± 0.39 PT: 3.88 ± 0.48	Control: 3.82 ± 0.38 PT: 3.29 ± 0.47 PT vs control***
					TOV (m/s)		Control: 1.17 ± 0.10 PT: 1.29 ± 0.18	Control: 1.10 ± 0.16 PT: 1.48 ± 0.15 PT vs control***
Rebutini et al. [17]	10 national level swimmers (7 M, 3 F) M: 22 ± 1.4 years; F: 21.3 ± 7.6 years M: 1.78 ± 0.06 m; 69.8 ± 4.8 kg F: 1.70 ± 0.05 m; 59.9 ± 2.9 kg	2×/week long jump training consisting of maximal horizontal and maximal long jumps; 9 weeks	Preferred technique	Best of 2 × maximal effort swim starts to 15 m under competition rules			Pre	Post
						sPFh (N)	837 ± 153	847.33 ± 164.23*
						IMP (N/s)	221.9 ± 61.6	242.5 ± 60.9*
					TOV (m/s)		1.93 ± 0.18	2.13 ± 0.28*
					hTOV (m/s)		1.84 ± 0.19	2.14 ± 0.21*
Rejman et al. [37]	9 national level swimmers (M) 21.9 ± 3.4 years 1.79 ± 0.001 m; 75.1 ± 6.6 kg	2× 60 min/week consisting of skips, bounds, hops and jumps; 6 weeks	Track start	Best of 3× swim start to 5 m			Pre	Post
					T5 m (s)		1.87	1.73***
					TOV (m/s)		1.88	2.14**
Resistance training								
Garcia-Ramos et al. [38]ᵃ	13 international level swimmers (5 M, 8 F) 18.1 ± 3.4 years 1.72 ± 0.08 m; 62.6 ± 8.5 kg	Variations of the squat, deadlift, hip thrust, leg flexion and extension exercises; 3 weeks	Kick start	Best of 2× swim starts to distance slightly further than 15 m			Pre	Post
					T10 m (s)		4.37 ± 0.42	4.47 ± 0.39*
					T15 m (s)		7.26 ± 0.51	7.54 ± 0.61*

F females, *hTOV* horizontal take-off velocity, *IMP* impulse, *M* males, *PT* plyometric training, *SD* standard deviation, *sPFh* starting peak horizontal forces, *T5 m* time to 5 m, *T5.5 m* time to 5.5 m, *T10 m* time to 10 m, *T15 m* time to 15 m, *TOV* take-off velocity

*$p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

[a] Only sea level data were included

provided on whether this was a concentric only SJ or a CMJ [30]. Furthermore, this study also had a very small sample size of seven swimmers and other important aspects of the methodology were somewhat unclear or did not reflect what is typically performed in the swim start. Notably, Pupisová and Pupis [30] stated in their methodology that the swim start was performed without any underwater kicks and had swimmers glide to 7 m and 9 m. This does not represent the typical action of a swimmer in the underwater phase of the swim start, where undulatory kicks are used to maintain as much entry velocity as possible [39].

4.2 Acute Changes in Swim Start Performance After Dry-Land Resistance Training Intervention

PAP can be described as a training method to improve muscle contractility, strength and speed in sporting performance by performing a small number of repetitions at maximal or near maximal effort, also referred to as conditioning activity (CA) [40], several minutes before an explosive activity [41, 42]. The use of PAP in the field of strength and conditioning has grown rapidly, with performance enhancement effects of PAP demonstrated in athletic movements such as jumping and sprinting [41]. The CA is able to potentiate the neuromuscular system, thereby allowing acute improvements in performance to be observed several minutes later as the acute fatigue from the CA diminishes [43]. Several mechanisms have been suggested for the acute PAP phenomenon, including greater recruitment of higher order motor units, increase in pennation angle and the phosphorylation of myosin regulatory light chains [44].

Four studies were identified that have examined the potential acute benefits of resistance training prior to swimming start performance, with three of these studies utilising a PAP approach [33–35]. Cuenca-Fernández et al. [35] demonstrated a positive PAP effect with respect to the time required to cover distances of 5 m and 15 m. It was also observed that a greater reduction in the time to 5 m and 15 m was observed after the use of the split stance lunge on the flywheel inertial device at maximal voluntary contraction than after the split stance lunge at 85% one repetition maximum (1RM) on the Smith machine. These results are consistent with the later study by Cuenca-Fernández et al. [34], who included the arm strokes, with one PAP protocol consisting of one set of three lunge and three arm stroke repetitions on the Smith machine at 85% of 1RM, while the other protocol comprised one set of four repetitions of both the upper and lower limb on a flywheel inertial device at maximum voluntary contraction. Both PAP protocols [34] demonstrated a shorter time to 5 m in comparison to a standard warm-up; however, there was no difference in the time to 5 m between those two interventions. Conversely, Kilduff et al. [33], who assessed the acute effects of one set of three repetitions of heavy, 87% of 1RM back squat on start performance, did not observe any significant reduction in the only time they recorded, i.e. the time to 15 m, but reported significant improvements in peak horizontal and peak vertical forces after PAP intervention.

Within the PAP literature, the kinematic and kinetic similarity between the CA and the subsequent movement has been reported to be an important factor, with studies in the sprint literature indicating greater PAP effects when movement patterns of the CA are followed by a biomechanically similar explosive activity [45, 46]. Thus, the utilisation of a split stance rather than traditional squat may further increase this PAP effect due to the PAP protocols being more biomechanically similar to the foot position and direction/timing of force application in the kick start technique on the OSB11 start block. The significant improvements in time to 5 m [34, 35] and 15 m [35] and peak horizontal and peak vertical forces [33] observed post PAP intervention suggest some benefits of using PAP as a pre-race warm-up to enhance a swimmer's swim start performance. However, the duration over which the potentiation effect lasts may be too short to be utilised as a component of pre-competition warm-ups in swimming competitions. A meta-analysis by Gouvêa et al. [40] of PAP on jumping performance has shown that an optimal PAP effect was found with a recovery period of 8–12 min after the preceding CA, with the PAP effect dissipating after a recovery period of 16 min or more. Specifically, Cuenca-Fernández et al. [34] utilised a rest period of 6 min and Cuenca-Fernández et al. [35] and Kilduff et al. [33] utilised a rest period of 8 min between the CA and the explosive activity, i.e. swim start. During competitions, swimmers may have to wait in marshalling areas for a period of up to 20 min after they complete their warm-up until they compete in their specific events. This could pose some current challenges as to how a PAP stimulus may be used to enhance swim start performance as a pre-competition warm-up strategy, especially as the successful PAP interventions identified in the current review have utilised heavy resistance training devices that would not be available in the marshalling areas.

In addition to using PAP to achieve short-term performance enhancement, it has been suggested that PAP can be manipulated to enhance the training stimulus of explosive strength exercises to induce greater chronic training-related adaptations than traditional resistance training exercises. The manipulation of PAP within a resistance training programme is also known as complex training [47]. Complex training combines heavier resistance training exercise with a lighter load power-oriented exercise in an attempt to transfer gains in strength to power [47]. The rationale for this complex pairing of exercises was that the heavy resistance strength-oriented set would provide an enhanced neural drive, which would then carry over to the lifting of the lighter resistance explosive exercise, resulting in a greater power output in the explosive exercise than would occur without the prior heavy resistance set [48]. PAP may be a viable training method when incorporated into a swimmer's regular dry-land resistance training programme and possibly contribute to enhanced swim start performance after several months of training. However, due to the lack of any such chronic PAP studies involving swimmers, future studies are required to document whether significant chronic adaptations in physical capacities and swim start performance can be observed after a PAP training programme.

Trunk stability is an important component in swimming as it allows for an efficient transfer of forces between the trunk and the upper and lower extremities to propel the body through the water and off the start blocks [49]. Weston et al. [50] have demonstrated chronic improvements in swimmers' core function and 50 m front crawl swim time with the implementation of a 12-week isolated trunk training programme. Within the scope of this review, Iizuka et al. [32] demonstrated significant acute improvements in swim start performance as a result of acute resistance training exercises for the trunk. The authors suggested that the trunk stabilisation exercises provided enhanced trunk stability which led to an immediate improvement in time to 5 m and average velocity over 5 m.

4.3 Changes in Swim Start Performance After Dry-Land Resistance Training Intervention

The combined use of dry-land resistance training and swim training is a common practice in competitive swimming [18, 51]. By overloading the muscles required for swimming with external resistances, a dry-land resistance training programme aims to increase the strength and power production of muscles that play important roles in competitive swimming events [52, 53]. Dry-land resistance training modalities can include ballistic training such as Olympic style lifts, e.g. cleans and their variations as well as plyometric activities, while non-ballistic training includes the use of free weight, bodyweight and/or machine-based exercises [18, 54]. Plyometric training refers to the performance of stretch–shortening cycle (SSC) movements involving a short-duration, high-velocity eccentric contraction followed by a rapid concentric contraction [55]. Athletes who can effectively use the SSC can produce significantly greater concentric force, velocity and power compared to what is possible in concentric only muscular contractions. The mechanisms contributing to this effect reflect specific neural adaptations of the SSC, the storage and utilisation of elastic strain energy, the stretch reflex and/or an increase in the active state of the muscle [56, 57]. Engaging in a plyometric training programme that requires fast muscular contraction of the lower body has been demonstrated to significantly improve swim start performance in all three studies identified in this systematic review [17, 36, 37], with significant improvements in key swim start parameters, such as time to 5 m and 5.5 m, take-off velocity and horizontal forces and impulse observed. As the swim start is a predominantly concentric movement, these specific training adaptations from the plyometric training studies would appear to be a direct result of the swimmers' ability to utilise the neural benefits of the SSC and rapidly develop concentric force, rather than their ability to utilise the SSC as a result of improvements in the athletes' eccentric strength capacity [55, 58]. In the study conducted by Rebutini et al. [17], the authors hypothesised that the long jumps performed in the training programme would be effective in improving the kinetics of the swim starts because they required the production of horizontal forces at similar velocities to the actual swim start. Such a hypothesis was consistent with the results of these studies, with significant increases in swim start horizontal take-off velocity, peak horizontal forces and/or horizontal impulse observed by Rebutini et al. [17] and time to 5 m and take-off velocity observed by Rejman et al. [37].

The available evidence on dry-land resistance training with free weights is limited. In this systematic review, we only found one study [38] that included resistance training exercises such as variations of the squat, deadlift, hip thrust, leg flexion and extension exercises, although such exercises appear to be commonly used by competitive swimmers. Results indicated no significant difference in swim start performance after the 3-week dry-land resistance training programme that was performed prior to the altitude training camp. When comparing results of this study involving resistance training exercises [38] to the three studies involving plyometric training [17, 36, 42], it was apparent that the 3 weeks of traditional resistance training was of substantially shorter duration than 6–9 weeks of plyometric training [17, 36, 37]. Furthermore, the swimmers were performing two swim sessions and one dry-land (some combination of resistance, cardiovascular and flexibility) session 6 days per week [38]. This 3-week resistance training programme involved a substantially greater weekly training load than the three plyometric studies. Due to these differences between the one traditional resistance training and three plyometric studies, it is difficult to determine on the basis of the current evidence whether plyometric, traditional resistance training or a combined approach may be most useful for improving swim start performance. Beyond the differences in training duration and weekly loads, it is also possible that the specificity principle may also underlie the potentially greater adaptations currently found for plyometric than traditional resistance training for improving swim start performance. Specifically, the more specific a training exercise is to a competitive movement, including the velocity, direction and time of force application, the greater the likely transfer of the training effect to performance [59, 60]. The studies by Rebutini et al. [17] and Rejman et al. [37] shared a key feature in their plyometric training programmes, which is an emphasis on the horizontal direction in the plyometric exercises performed. Rebutini et al. [17] included long jumps in their plyometric training intervention, and Rejman et al. [37] modified the starting position of the plyometric exercises to better simulate the swimming start and to emphasise a greater horizontal direction of take-off. The improvements in swim start performance observed with all three plyometric studies [17, 36, 37] appear to be indicative of the potential for different forms of plyometric training to elicit significant improvements in swimming start performance with as little as 6–9 weeks of training.

4.4 Methodological Considerations

4.4.1 Measurement of the Swim Start

Of the eight cross-sectional and eight intervention studies included in this systematic review, only four studies [31, 32, 35, 38] utilised the kick start technique and the OSB11 start block that is currently used in competitive swimming. Even though the track start utilised in four [27, 30, 37, 61] out of the 16 studies included in this systematic review may have some similarities to the kick start technique currently used in competitive swimming, Honda et al. [16] have identified that the additional kick plate on the OSB11 start block is capable of significantly improving both time to 5 m and 7.5 m, with a further 0.04-s improvement obtained in the kick start compared to the track start technique at both distances. This is attributed to an increase in horizontal force production that is able to be produced by the rear leg on the kick plate of the OSB11 starting block, which ultimately increases horizontal take-off velocity [16].

The eight cross-sectional studies included in the review exhibited some degree of inconsistency with the measurement of the swim start performance kinematic measures, such as the time to set distances of 5, 10 and/or 15 m. The majority of the studies [4, 27, 28, 31] measured swim start time when the head crossed the specified distances in their study. Two studies [61, 62] measured swim start time when the fingertips crossed 10 m, with the two other studies [29, 30] not specifying how the start time to 15 m was measured. For the intervention studies, four intervention studies [17, 34, 35, 38] measured the time to set distances when the head crossed the specified distance, while Iizuka et al. [32] measured the time to 5 m when the fingertips crossed 5 m. Despite reporting the same measure of the time to distances of 5 m and 5.5 m, there appears to be a discrepancy in the values reported between the training intervention study by Rejman et al. [37] and Bishop et al. [36]. This is due to the difference in how the swim start was quantified in both studies. Rejman et al. [37] quantified time to 5 m from the time from the final shift of centre of mass from the edge of the starting block to a distance of 5 m, whereas Bishop et al. [36] recorded time to 5.5 m using the time from starting stimulus to the point in time at which the head made contact with the water surface.

There also appear to be some differences in the nature of the swim task performed across these studies. Within this review, the majority of the studies tested the swimmers under competition rules [4, 17, 27–29, 33–36, 61, 62]. In contrast, some studies included a dive and glide test [30, 37], while Garcia-Ramos [31] had swimmers perform undulatory kicks until 15 m. Therefore, it is possible that the variety of swim start methodologies used may have had significant implications in the comparison of results between studies.

4.4.2 Strength Diagnostics

Tests of muscular strength and/or power qualities are commonly performed to assess training-induced changes and the efficacy of a strength and conditioning programme in many athletic populations [63]. For sports requiring high to very high levels of muscular strength, maximal and submaximal strength assessments or isometric assessments such as the isometric mid-thigh pull are commonly used [63]. For dynamic performance qualities, vertical lower body jumping exercises are common measurement tools of athletic lower body force and power ability [64].

The majority of the cross-sectional studies [4, 27–31, 62] and one intervention study [38] identified in this systematic review utilised dynamic lower body exercises such as the CMJ and SJ as a measurement of lower body power. Only two of eight cross-sectional studies [4, 29] and four of eight intervention studies [17, 33–35] included any maximal strength assessments. The relative lack of maximal strength assessments compared to explosive total body jumping exercises in this systematic review may reflect the task demands of the swim start whereby high levels of lower body power rather than maximal muscle strength are required to enhance swim start performance.

4.4.3 Study Population

The magnitude of difference in strength characteristics and response to a resistance training programme can be affected by sex, age and training status [65]. The majority of the studies reviewed generally consisted of a small sample size and a potentially greater bias towards male compared to female participants. Only two of the cross-sectional studies had all female swimmers, and the four studies that had a mix of females and males had an uneven split of both sexes, with a greater number of male participants compared to females. In addition, the majority of studies did not provide any clear description of the resistance training experience or the baseline levels of lower body muscular strength of their participants. Specifically, only two [4, 29] out of the eight cross-sectional and three acute intervention studies [33–35] included any details regarding the baseline strength level of the swimmers. As such, it is difficult to determine how sex, age and training status may influence the relationship and/or training response between dry-land jump performance and swim start performance.

4.4.4 Study Design

With respect to the intervention studies, one factor for potential bias could be the research design and statistical analyses used in the studies. Only one [36] out of the eight intervention studies identified utilised a controlled trial design with an intervention and control group, with the remainder of the studies using a within group pre–post test statistical comparison using ANOVA or paired *T* tests.

The lack of control groups and the use of a within-group statistical analysis approach in the intervention studies make it difficult to determine whether the improvements in swim start performance were a result of the dry-land resistance training intervention or whether they were related to the overall swim training programme. One possible reason for the lack of randomised controlled trials may reflect the relatively limited sample size of high-performance swimming squads.

5 Conclusion

Within the limits of the review, the current literature indicates that a range of lower body strength and power measures are highly correlated with swim start performance, and these correlations appear greatest when utilising bodyweight vertical jumping exercises. These findings would suggest that assessing vertical jump performance would be a better diagnostic tool to assess lower body power capabilities than traditional strength assessments for swim start performance. Significant acute and chronic swim start performance benefits can be obtained using a PAP training protocol and lower body plyometric exercises that are primarily horizontal in direction, respectively. Despite the relative homogeneity of participants in the studies included in this review, the results across intervention studies suggest that significant improvements in swim start performance can be obtained from both a PAP training protocol and plyometric exercises independent of skill level.

Due to the relative lack of research with the currently used OSB11 starting block and kick start technique, future cross-sectional and intervention studies should utilise the current start block and start technique to confirm that the findings highlighted in this review apply to current practices in competitive swimming. Given that swimmers simultaneously integrate swim training and dry-land resistance training within a periodised programme to develop muscular strength and power capabilities [18, 54], additional research should also compare the potential benefits of different dry-land resistance training approaches to provide better understanding of the development of strength and conditioning programmes more conducive to improving swim start performance.

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Compliance with Ethical Standards

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APPENDIX 6: AUSSPORTMED, EMBASE, MEDLINE (OVID), SPORTDISCUS, AND WEB OF SCIENCE SEARCH STRATEGY (CHAPTER 3)

Search 1: AussportMed

(((Resistance OR strength OR weight*) AND (train* OR exercise* OR lifting)) OR Jump* OR plyometric* OR PAP OR "post-activation potentiation" OR CMJ or dryland OR dry-land OR cross-training OR "resistance band") AND (start* OR block* OR Force OR Reaction OR Power OR "Take-off" OR "time to" OR RFD) AND (swim*)

Search 2: Embase

(((Resistance OR strength OR weight*) AND (train* OR exercise* OR lifting)) OR 'resistance training'/exp OR Jump* OR plyometric* OR 'plyometrics'/exp OR PAP OR “post-activation potentiation” OR CMJ or dryland OR dry-land OR cross-training OR “resistance band”) AND (start* OR block* OR Force OR Reaction OR Power OR “Take-off” OR “time to” OR RFD) AND ('swimming'/exp OR swim*)

Search 3: Medline (Ovid)

(((Resistance OR strength OR weight*) **AND** (train* OR exercise* OR lifting)) OR exp Resistance Training/ OR Jump* OR plyometric* OR exp PLYOMETRIC EXERCISE/ OR PAP OR "post-activation potentiation" OR CMJ or dryland OR dry-land OR cross-training OR "resistance band") AND (start* OR block* OR Force OR Reaction OR Power OR "Take-off" OR "time to" OR RFD) AND (swim* OR exp Swimming/) not (exp animals/ not humans.sh.)

Search 4: SPORTDiscus

(((Resistance OR strength OR weight*) AND (train* OR exercise* OR lifting)) OR DE "STRENGTH training" OR DE "WEIGHT lifting" OR Jump* OR plyometric* OR PAP OR "post-activation potentiation" OR CMJ or dryland OR dry-land OR cross-training OR "resistance band") AND (start* OR block* OR Force OR Reaction OR Power OR "Take-off" OR "time to" OR RFD) AND (swim* OR DE “SWIMMING”)

Search 5: Web of Science

(((Resistance OR strength OR weight*) AND (train* OR exercise* OR lifting)) OR Jump* OR plyometric* OR PAP OR "post-activation potentiation" OR CMJ or dryland OR dry-land OR cross-training OR "resistance band") AND (start* OR block* OR Force OR Reaction OR Power OR "Take-off" OR "time to" OR RFD) AND (swim*) *NOT* TOPIC: (animal OR rat OR rats OR mouse OR mice)

APPENDIX 7: THE PREDICTION OF SWIM START PERFORMANCE BASED ON SQUAT JUMP FORCE-TIME CHARACTERISTICS – PUBLISHED VERSION

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The prediction of swim start performance based on squat jump force-time characteristics

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ABSTRACT

Background. Depending on the stroke and distances of the events, swim starts have been estimated to account for 0.8% to 26.1% of the overall race time, with the latter representing the percentage in a 50 m sprint front crawl event (*Cossor & Mason, 2001*). However, it is still somewhat unclear what are the key physiological characteristics underpinning swim start performance. The primary aim of this study was to develop a multiple regression model to determine key lower body force-time predictors using the squat jump for swim start performance as assessed by time to 5 m and 15 m in national and international level swimmers. A secondary aim was to determine if any differences exist between males and females in jump performance predictors for swim start performance.

Methods. A total of 38 males (age 21 ± 3.1 years, height 1.83 ± 0.08 m, body mass 76.7 ± 10.2 kg) and 34 females (age 20.1 ± 3.2 years, height 1.73 ± 0.06 m, body mass 64.8 ± 8.4 kg) who had competed at either an elite ($n = 31$) or national level ($n = 41$) participated in this study. All tests were performed on the same day, with participants performing three bodyweight squat jumps on a force platform, followed by three swim starts using their main swimming stroke. Swim start performance was quantified via time to 5 m and 15 m using an instrumented starting block.

Results. Stepwise multiple linear regression with quadratic fitting identified concentric impulse and concentric impulse^2 as statistically significant predictors for time to 5 m ($R^2 = 0.659$) in males. With time to 15 m, concentric impulse, age and concentric impulse^2 were statistically significant predictors for males ($R^2 = 0.807$). A minimum concentric impulse of 200–230 N.s appears required for faster times to 5 m and 15 m, with any additional impulse production not being associated with a reduction in swim start times for most male swimmers. Concentric impulse, Reactive strength index modified and concentric mean power were identified as statistically significant predictors for female swimmers to time to 5 m ($R^2 = 0.689$). Variables that were statistically significant predictors of time to 15 m in females were concentric impulse, body mass, concentric rate of power development and Reactive strength index modified ($R^2 = 0.841$).

Discussion. The results of this study highlight the importance of lower body power and strength for swim start performance, although being able to produce greater than 200 or 230 N.s concentric impulse in squat jump did not necessarily increase swim start

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Additional Information and Declarations can be found on page 14

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performance over 5 m and 15 m, respectively. Swimmers who can already generate greater levels of concentric impulse may benefit more from improving their rate of force development and/or technical aspects of the swim start performance. The sex-related differences in key force-time predictors suggest that male and female swimmers may require individualised strength and conditioning programs and regular monitoring of performance.

Subjects Kinesiology
Keywords Swimming, Strength and conditioning, Resistance training, Swim start, Dry-land

INTRODUCTION

Swim start performance has been identified as a determining factor for success, especially in sprint distance events, as it is the part of the race that the swimmer is travelling at the fastest velocity (*Cossor & Mason, 2001*; *Tor, Pease & Ball, 2014*). While the exact nature of starts may differ between the four swimming strokes, there are three primary phases that contribute towards the overall start performance. The block phase requires a quick reaction to the starting signal and a large take-off velocity that is primarily horizontal in direction (*Garcia-Hermoso et al., 2013*). The subsequent flight phase is an example of projectile motion, whereby the swimmer becomes airborne and finishes when they contact the water (*Slawson et al., 2013*; *Tor, Pease & Ball, 2014*). The flight phase is followed by the underwater phase, in which swimmers attempt to maintain a streamlined position with their arms outstretched in front of the head to minimise velocity loss while also performing multiple propulsive undulatory leg kicks (except in breaststroke) until their head resurfaces before the 15 m mark (*Formicola & Rainoldi, 2015*). The block, flight, and underwater phase account for approximately 11%, 5%, and 84% respectively of the total start time (*Slawson et al., 2013*). The average velocity during the underwater phase is highly dependent on the take-off velocity acquired in the block phase, the horizontal distance obtained in the flight phase, as well as the degree of streamlining and effectiveness of the undulatory leg kicks during the underwater phase (*Tor, Pease & Ball, 2014*).

As close margins often exist between medallists in sprint swimming events, being able to identify areas to achieve marginal gains in performance by tenths or even hundredths of a second can make a difference in overall performance (*Bishop et al., 2009*). Previous research has highlighted a key component of swim start performance is the ability to produce high forces off the starting block. In a recent systematic review of eight cross-sectional studies, *Thng, Pearson & Keogh (2019)* observed significant correlations between vertical jump and lower body strength scores to swim start performance in swimmers of a variety of standards, with these correlations typically higher for the jump than strength tests. Specifically, near perfect correlations ($r > 0.90$) between jump height or take-off velocity and swim start performance were observed in the eight studies. These results highlight the importance of lower body power and strength as an important component of swim start performance. However, out of the 8 cross-sectional studies identified in the systematic review (*Thng, Pearson & Keogh, 2019*), only one study utilised the OSB11 start block (OMEGA, Zurich, Switzerland) that is currently used in competitive swimming (Garcia-Ramos et al., 2016a). The OSB11 start block which was introduced by FINA in 2010 has an angled kick plate at the rear of the block that allows the swimmer to adopt a kick start technique. Honda et al. (2010) have identified that the angled kick plate on the OSB11 start block is capable of significantly improving both time to 5 m and 7.5 m, with a further 0.04 s improvement obtained in the kick start compared to the track start technique performed on the previous starting block. This is attributed to an increase in horizontal force application and subsequent take-off velocity from the additional contribution of the rear leg on the kick plate. This view of Honda et al. (2010) was consistent with the findings of Slawson et al. (2013) who observed higher peak horizontal and vertical force generation with the OSB11 start blocks in elite swimmers, with these forces significantly correlated to a better start performance as assessed by block time, take-off velocity and flight distance.

In addition, all of the studies described in the systematic review by Thng, Pearson & Keogh (2019) only involved correlational analyses. While correlations describe the nature of a relationship between two variables, other statistical approaches such as multiple linear regression may provide more information regarding what power and strength variables (hereafter referred to as force-time characteristics) of jumping performance that best predict swim start performance in high performance swimmers. The lack of research using the OSB11 start block and kick start technique in these correlation studies needs to be addressed, as this relative lack of ecological validity with the start technique used in seven of the eight published studies may limit the generalisability to contemporary high-performance swimming.

Another limitation of the previous literature is the small sample sizes of recreational to sub-elite swimmers ($n = 7–27$) and the relative focus on male swimmers at the expense of their female counterparts. This is a concern as previous research has established differences in force and power capabilities between males and females in other athletic activities (McMahon, Rej & Comfort, 2017; Rice et al., 2017). For example, a number of studies has observed that males are able to produce higher velocities at the same percent of one repetition maximum and have a greater rate of force development and countermovement jump height than females (Laffaye, Wagner & Tombleson, 2014; McMahon, Rej & Comfort, 2017; Rice et al., 2017; Torrejon et al., 2019). Rice et al. (2017) concluded that this greater jump height observed in males compared to females can be attributed to larger concentric impulse and thus greater velocity throughout most of the concentric phase at take-off in the countermovement jump. Further, the higher rate of force development and ability to produce greater velocities at the same percentage of one repetition maximum in males may be a result of greater muscle thickness and cross-sectional area, greater percentage of fast-twitch muscle fibres, greater concentration of anabolic hormones and higher neural activity during muscle contractions compared to females (Alegre et al., 2009). From a practical standpoint, these sex-related differences in force-time characteristics suggests there might need to be some potential differences in aspects of athletic monitoring and strength and conditioning programs between high-performance male and female swimmers.

The primary objective of this study was to develop a multiple regression model to determine key lower body force-time predictors for swim start performance using the squat jump in high performance swimmers. Considering the potential sex differences in force-time characteristics during jumping, a secondary aim was to determine if differences exists between males and females in jump performance predictors for swim start performance.

MATERIALS & METHODS

Study design

A cross-sectional study design was used to quantify the relationship between squat jump (SJ) force-time variables to swim start performance as assessed by times to 5 m and 15 m in national and international level swimmers. All tests were performed on the same day, with participants first performing SJ testing on the force platform, followed by a swim start performance test with a 30-minute recovery period in between each testing session.

Participants

Thirty-eight males and 34 females who had competed at either an elite ($n = 31$) or national level ($n = 41$) in front crawl, butterfly or breaststroke participated in this study. Backstroke was excluded due to the start being initiated from within the water, instead of on the elevated OSB11 starting block. Elite level swimmers comprised of swimmers who had competed internationally in either the Olympics, Commonwealth Games or World Championships. National level swimmers comprised of swimmers that have at least 2 years of experience in competing at a national level and competed at the most recent national championships. Swimmers were required to have at least 1 year of land-based resistance training experience under the supervision of a strength and conditioning coach. All participants gave written informed consent to participate in the study, which was conducted in accordance with the Declaration of Helsinki and approved by Bond University Human Research Ethics Committee (0000016006), The University of Queensland Human Research Ethics Committee (HMS17/41) and Swimming Australia Ltd.

Methodology

Squat jump test

Prior to the SJ test, participants completed a dynamic lower body warm-up under the supervision of a strength and conditioning coach. Following the warm-up, participants were given two practice jumps before the test was conducted. Jumps were performed on a force platform (ForceDecks FD4000, London, United Kingdom), with a sample rate of 1,000 Hz. Participants started in an upright standing position with their hands on their hips. They were then instructed to adopt a squat position using a self-selected depth that was held for 3 s before they attempted to jump as high as possible (*Mitchell et al., 2017*). A self-selected squat depth was chosen as it has been reported to produce the greatest jump height and higher peak force outputs in comparison to measured squat depths (*Kirby et al., 2011*). A successful trial was one that did not display any small amplitude countermovement at the start of the jump phase on the force trace (*Sheppard & Doyle, 2008*). All participants were asked to perform three maximal intensity SJ with a 30-second passive rest in between each effort.

The SJ trial with the highest jump height was kept for data analysis. Jump height was determined by the conventional impulse-momentum method (Jump Height $= v^2/2g$, where $v =$ velocity at take-off and $g =$ gravitational acceleration) (*Heishman et al., 2019*). Ground reaction force data from the SJs were analysed using the commercially available ForceDecks software (ForceDecks, London, United Kingdom). Out of the variables provided by ForceDecks, 46 variables, excluding any left-to right asymmetry variables were initially extracted for use in further analysis. Descriptions of the SJ variables are provided in the Electronic Table S1.

Swim start

After completing a self-selected warm-up based on their usual pre-race warm-up routine, participants then performed three maximal effort swim starts with their main swim stroke (front crawl ($n = 50$), butterfly ($n = 12$), or breaststroke ($n = 10$)) while wearing their regular swim training swimsuits. Trials were started as per competition conditions and swimmers were instructed to swim to a distance past the 15 m mark, in order to ensure that representative values at the 15 m distance were obtained (*Barlow et al., 2014*). Two-minutes of passive recovery was given between each trial (*Tor, Pease & Ball, 2015b*). The start with the fastest time to 5 m for each individual with all swim strokes were selected for further analysis.

All 72 participants were included in the time to 5 m analysis irrespective of stroke performed, as the technical execution of the swim start does not differ until after 5 m. To avoid the potential confounding influence of the speed differences in both the underwater and swim phases of butterfly and breaststroke, only front crawl was included for time to 15 m analysis as it comprised of majority of the sample ($n = 50$).

Swim start performance were collected using a Kistler Performance Analysis System—Swimming (KPAS-S, Kistler Winterthur, Switzerland), which utilises a force instrumented starting block, constructed to match the dimensions of the Omega OSB11 block (KPAS-S Type 9691A1; Kistler Winterthur, Switzerland). Time to 5 m and 15 m were collected using five calibrated high speed digital cameras collecting at 100 frames per second, synchronised to the instrumented starting block using the KPAS-S. One camera was positioned 0.95 m above the water and 2.5 m perpendicular to the direction of travel to capture the start and entry of swimmer into the water, while the other three cameras were positioned 1.3 m underwater at 5 m, 10 m and 15 m perpendicular to the swimmer to capture the time to 15 m (Fig. 1) (*Tor, Pease & Ball, 2015b*). The times to 5 m and 15 m were defined as the time elapsed from the starting signal until the apex of the swimmers' head passed the respective distances (*Tor, Pease & Ball, 2015b*). An Infinity Start System (Colorado Time Systems, Loveland, Colorado, USA) provided an audible starting signal to the athletes as well as an electronic start trigger to the KPAS-S system.

Statistical analysis

Descriptive statistics are reported as mean ± SD for normally distributed continuous variables and frequency (%) for categorical variables. Normality was checked using histograms, normal Q-Q plots and the Shapiro–Wilk test. A principal component

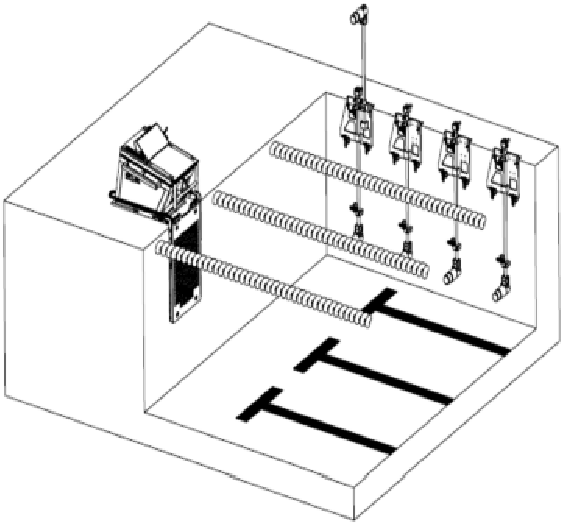

Figure 1 **Overview of the camera set-up and instrumented starting block** (*Kistler Group, 2019*).
Full-size DOI: 10.7717/peerj.9208/fig-1

analysis (PCA) was used to identify optimal sets of key performance indicators on the 46 jump variables extracted from ForceDecks force platform (ForceDecks, London, United Kingdom). This method has been used in previous studies that sought to identify kinematic and kinetic predictors of athletic performance from a number of highly interrelated vertical jump performance measures (*Kollias et al., 2001*; *Laffaye, Bardy & Durey, 2007*). A second PCA was conducted to explore the reduced dataset of 32 jump performance variables and identify the principal components (PC) summarising the primary force-time variables. The decision on a suitable number of PCs to retain in each PCA required eigenvalues of 1.0 or greater (Kaiser criterion) and was supported using a scree plot.

Multiple linear regression models using a stepwise regression method were initially performed to identify the potential predictors of the outcome variables of time (s) to 5 m and 15 m. Analyses were carried out on the entire dataset, and also on the data split by sex. Second order polynomial models were also investigated, as visual inspection identified that these quadratic models better matched the data for males than the linear models, with this also confirmed by significantly higher R^2 for the quadratic models (*Bobrovitz & Ottenbacher, 1998*; *Park, Marascuilo & Gaylord-Ross, 1990*). Collinearity diagnostics were used to avoid the problem of multicollinearity. The assumptions of normality, linearity and homoscedasticity of residuals were verified. Results of the regression modelling are presented in terms of unstandardized coefficients, the 95% CI and *p*-values, along with the R^2 and standard error of estimate. Data were analysed with statistical software R version 3.5.3 and SPSS version 23.0.0 (SPSS Inc., Chicago, IL). *P*-values less than 0.05 were deemed to indicate statistical significance.

Table 1 Physical characteristics of participants. All data is presented as means and standard deviations.

Variables	Males		Females	
	5 m ($n = 38$)	15 m ($n = 26$)	5 m ($n = 34$)	15 m ($n = 24$)
Age (years)	21.0 ± 3.1	21.2 ± 3.2*	20.1 ± 3.2	19.2 ± 3.2
Body mass (kg)	76.7 ± 10.2**	76.5 ± 11.0**	64.8 ± 8.4	64.2 ± 8.4
Height (m)	1.83 ± 0.08**	1.85 ± 0.08**	1.73 ± 0.06	1.73 ± 0.06
Time to 5 m (s)	1.48 ± 0.09**		1.65 ± 0.08	
Time to 15 m (s)		6.4 ± 0.44**		7.3 ± 0.5

Notes.

$^{*}p < 0.05$.

$^{**}p < 0.001$ between males and females.

RESULTS

Seventy-two swimmers, comprising 38 males and 34 females were included in this study. The physical characteristics of the participants are described in Table 1. Out of the 72 participants, 50 participants performed the swim start using the front crawl technique, with an additional 12 participants performing butterfly and 10 participants using breaststroke. Statistically significant differences among males and females were observed in a number of variables (Table 1), with males significantly heavier, taller and faster to 5 m and 15 m than females.

In the first PCA analysis on the 46 jump variables extracted from ForceDecks force platform (ForceDecks, London, United Kingdom), four PCs which explained 82% of the variance were identified. Thirty-two most influential jump variables were identified from this initial PCA. A secondary PCA was run to explore the new dataset of 32 jump performance variables. The first three components, which explained 93% of the variance, were retained. From this set, 15 variables were identified as potential predictors in subsequent regression models (Table 2). The results revealed that Component 1 accounting for 67.5% of the variance, was of predominantly kinetic component. Component 2 accounting for 17.1% of the variation, was predominantly a time-dependent kinematic component. Lastly, Component 3 accounted for 8.5% of the variation, with the highest load attributed to bodyweight.

Linear stepwise multiple regression analyses were performed using the ForceDecks SJ data to predict time to 5 m (see Fig. 2 and Table 3) and time to 15 m (see Fig. 3 and Table 4) in the overall sample of males and females as well as male and female subgroups.

Time to 5 m

The scatterplot in Fig. 2 shows a quadratic relationship between SJ concentric impulse and time to 5 m in males ($R^2 = 0.693$). For a fast time to 5 m for males, visual inspection of the data suggests a minimum concentric impulse production of around 180–200 N.s is required. While visual inspection of the model suggested no additional reduction in time to 5 m with a higher concentric impulse for most swimmers, there are some outlier individuals who appear to derive additional performance benefit from an increased concentric impulse up to approximately 230 N.s. The relationship between concentric impulse and time to

Table 2 List of 15 most influential potential predictors of swim start performance identified from the PCA and their correlations with the principal components.

Potential predictors	Principal Component		
	PC1	PC2	PC3
Variation explained for each component	**67.5%**	**17.1%**	**8.5%**
Bodyweight (BW)	−0.71	0.11	0.68
Concentric impulse	−0.88	0.31	0.34
Concentric mean force	−0.91	−0.09	0.39
Concentric mean power	−0.94	0.13	0.14
Concentric peak force	−0.92	−0.15	0.32
Concentric rate of power development (RPD)	−0.93	−0.31	0.04
Force at peak power	−0.92	−0.05	0.33
Peak power	−0.95	0.24	0.14
Reactive strength index modified (RSImod)	−0.90	−0.12	−0.20
Take-off peak force	−0.92	−0.15	0.32
Concentric peak velocity	−0.77	0.55	−0.29
Concentric rate of force development (RFD) BW	−0.59	−0.75	−0.15
Concentric RFD	−0.72	−0.66	0.05
Jump height (impulse-momentum)	−0.75	0.56	−0.31
Velocity at peak power	−0.68	0.66	−0.27

Table 3 Multiple linear regression models to predict swim start time (s) to 5 m performance in females, males and both females and males combined.

		% contribution	Beta coefficient (95% CI)	*p*- value
All	Concentric Impulse (N.s)	70.4	−0.002 (−0.002 to −0.001)	<0.001
	Sex (Females)	5.4	0.065 (0.028 to 0.102)	0.001
	RSImod (m/s)	1.5	−0.084 (−0.164 to −0.004)	0.040
	Constant		1.882 (1.790 to 1.974)	<0.001
	R^2 (SEE)		0.773 (0.059)	
Females	Concentric impulse (N.s)	51.6	−0.003 (−0.004 to −0.002)	<0.001
	RSImod (m/s)	9.5	−0.209 (−0.315 to −0.104)	<0.001
	Concentric Mean Power (W)	7.8	0.0002 (0.00004 to 0.0003)	0.010
	Constant		2.103 (1.986 to 2.219)	<0.001
	R^2 (SEE)		0.689 (0.047)	
Males	Concentric Impulse (N.s)	53.6	−0.010 (−0.015 to −0.005)	<0.001
	Concentric Impulse^2 (N.s)^2	12.3	0.00002 (0.00001 to 0.00003)	0.001
	Constant		2.645 (2.167 to 3.124)	<0.001
	R^2 (SEE)		0.659 (0.055)	

Notes.
SEE, standard error of estimate.

5 m observed in females was linear ($R^2 = 0.487$), but this relationship was affected by other factors outlined in Table 3.

Concentric impulse was a statistically significant predictor in all three regression models (Table 3). The best prediction equations for time to 5 m in females and males were as

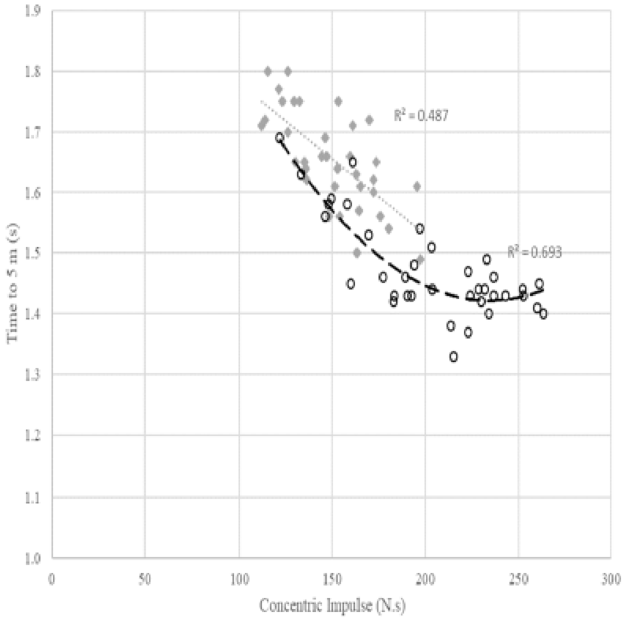

Figure 2 Relationship between concentric impulse (N.s) against time to 5 m (s) across females and males. Poly means polynomial regression to order 2, i.e., quadratic. The grey dotted line and diamond markers represent the linear relationship between concentric impulse and time to 5 m in females. The dashed line with circle markers represents the quadratic relationship between concentric impulse and time to 5 m in males.

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follows:

$$\text{Females}: \text{T5 m (s)} = 2.103 - 0.003\ (\text{concentric impulse}) - 0.209\ (\text{RSImod}) \\ +0.0002\ (\text{concentric mean power})$$

$$\text{Males}: \text{T5 m (s)} = 2.645 - 0.010\ (\text{concentric impulse}) \\ +0.00002\ (\text{concentric impulse})^2.$$

Time to 15 m

The scatterplot in Fig. 3 shows a quadratic relationship between SJ concentric impulse and time to 15 m in males ($R^2 = 0.746$). For a fast time to 15 m in males, a minimum concentric impulse production of around 230 N.s is required. However, similar to Fig. 2, the relationship between concentric impulse and time to 15 m observed in females was linear ($R^2 = 0.651$) but this relationship was also affected by other factors presented in Table 4.

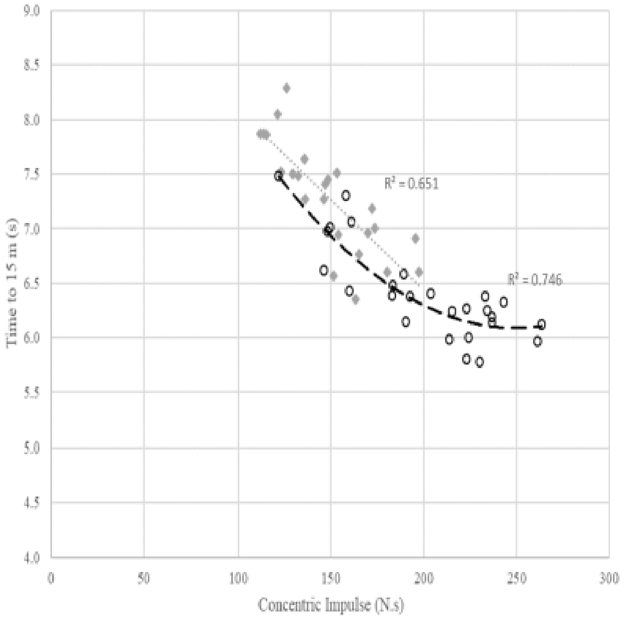

Figure 3 Relationship between concentric impulse (N.s) against time to 15 m (s) across females and males. Poly means polynomial regression to order 2, i.e., quadratic. The grey dotted line and diamond markers represent the linear relationship between concentric impulse and time to 15 m in females. The dashed line with circle markers represents the quadratic relationship between concentric impulse and time to 15 m in males.

Full-size DOI: 10.7717/peerj.9208/fig-3

The SJ concentric impulse was also the main significant predictor in all three regression models of the time to 15 m (Table 4). The best regression models were as follows:

$$\text{Females}: \text{T15 m (s)} = 9.303 - 0.030\ (\text{concentric impulse}) + 0.035\ (\text{bodymass})$$
$$+0.0002\ (\text{concentric RPD}) - 1.714\ (\text{RSImod})$$

$$\text{Males}: \text{T15 m (s)} = 11.188 - 0.033\ (\text{concentric impulse}) - 0.048\ (\text{age})$$
$$+0.00007\ (\text{concentric impulse})^2.$$

DISCUSSION

The present study revealed that several lower body force-time characteristics, in particular concentric impulse, were significantly related to swim start performance in national and international level swimmers. However, when these analyses were performed for each sex individually, several differences in the prediction of swim start performance were observed. These sex-related differences in key force-time characteristics suggest that strength and

Table 4 **Multiple linear regression models to predict swim start time (s) to 15 m performance in females, males and both females and males combined.**

		% contribution	Beta coefficient (95% CI)	*p* value
All	Concentric Impulse (N.s)	76.1	−0.008 (−0.011 to −0.004)	<0.001
	Age (years)	3.5	−0.052 (−0.087 to −0.018)	0.004
	Sex (female)	3.0	0.362 (0.151 to 0.572)	0.001
	Constant		9.074 (8.503 to 9.646)	<0.001
	R^2 (SEE)		0.826 (0.278)	
Females	Concentric Impulse (N.s)	65.1	−0.030 (−0.041 to −0.020)	<0.001
	Body mass (kg)	9.3	0.035 (0.006 to 0.064)	0.020
	Concentric RPD (W/s)	4.9	0.0002 (0. 00006 to 0.0003)	0.004
	RSImod (m/s)	4.8	−1.714 (−3.215 to −0.213)	0.027
	Constant		9.303 (8.398 to 10.208)	<0.001
	R^2 (SEE)		0.841 (0.225)	
Males	Concentric Impulse (N.s)	66.6	−0.033 (−0.058 to −0.008)	0.011
	Age (years)	9.4	−0.048 (−0.086 to −0.010)	0.016
	Concentric Impulse ^{2} (N.s)^2	4.7	0.00007 (0.000007 to 0.0001)	0.031
	Constant		11.188 (8.975 to 13.401)	<0.001
	R^2 (SEE)		0.807 (0.205)	

conditioning programs and regular monitoring of performance may need to be tailored to male and female swimmers.

In the swim start, swimmers have to apply large forces rapidly on the start block to maximise horizontal take-off velocity, which in turn allows them to travel farther horizontally in the air before entering the water (*Rebutini et al., 2014*). This task demand is consistent with the impulse-momentum relationship, whereby an impulse (the product of force and time of force application) needs to be generated to cause a change in momentum (i.e., velocity) of the system (*Schilling, Falvo & Chiu, 2008*). An analysis by *Tor, Pease & Ball (2015a)* of the above water parameters in the swim start have found that take-off velocity and time on block were key predictors of swim start performance as assessed by time to 15 m using the OSB11 start block. Strong positive correlations between peak forces in the countermovement jump and peak forces on the OSB11 start block have also been reported by Cossor and colleagues (*Cossor et al., 2011*). Thus, to be able to achieve a high take-off velocity, a swimmer needs to be able to apply high forces/ impulses off the starting block. Given that the swim start is mainly a concentric only movement, the findings of the present study further emphasise the important association between a swimmers' ability to produce impulse in the SJ and swim start performance.

It was expected that the current study would demonstrate a stronger prediction to 5 m than 15 m in the swim start. This hypothesis was based on how the movement pattern in the SJ is similar to the initial push-off in the block phase as well as the findings of *Garcia-Ramos et al. (2016b)* and *Benjanuvatra, Edmunds & Blanksby (2007)*, who reported a significant correlation in take-off velocity (*Garcia-Ramos et al., 2016b*) and jump height (*Benjanuvatra, Edmunds & Blanksby, 2007*) in the SJ to 5 m ($r = -0.56$ and $r = -0.92$ respectively) but not 15 m. In contrast to this initial hypothesis, the current study demonstrated that the SJ force-time variables explained a greater amount of variance in time to 15 m than time to 5 m. Results of the current study were also consistent with *Garcia-Ramos et al. (2016a)* who observed that the correlations between jump height and swim start performance were greater for the time to 15 m ($r = -0.67$) than time to 5 m ($r = -0.55$) using the kick start technique. Such equivalence in the literature was surprising, but it is possible that these contrasting findings from the current study to the limited literature could be attributed to a variety of between study differences, including the swim start technique and start block, as well as the sample size and homogeneity of participants included in the previously published studies. The current study utilised the kick start technique on the OSB11 start block, whereas *Benjanuvatra, Edmunds & Blanksby (2007)* and *Garcia-Ramos et al. (2016b)* utilised the grab start and track start, respectively. In addition, both of these studies included only female swimmers and had substantially smaller sample sizes ($n = 20$ and $n = 7$), whereas the current study utilised a mix of male and female swimmers, with a larger sample size for both time to 5 m ($n = 72$) and 15 m ($n = 50$). As previously mentioned, the underwater phase is a key parameter in swim start performance, as a swimmer spends the highest percentage of the start in the underwater phase for all swim strokes (*Cossor & Mason, 2001*; *Tor, Pease & Ball, 2015a*; *Vantorre et al., 2010*). *Garcia-Ramos et al. (2016b)* have suggested that swimmers require high levels of lower body strength and power to maximise their underwater kick performance. Therefore, it is possible that the stronger prediction in time to 15 m than 5 m in this study and the study by *Garcia-Ramos et al. (2016a)* may reflect the commonality in lower body force-time characteristics required for the block phase with the kick start technique and the undulatory kicks performed during the underwater phase.

Another focus of this study was examining potential sex-related differences in the force-time characteristics that may underpin swim start performance in high-performance swimmers. While concentric impulse was the strongest predictor for time to 5 m and 15 m in both males and females, the current study identified some differences between the sexes with respect to the predictors of time to 5 m and 15 m. For a quick time to 5 m and 15 m in males, a minimum concentric impulse of 200–230 N.s appears required, with any additional impulse production not being associated with a reduction in swim start times for most male swimmers. However, it is worth noting that within the dataset, there appear to be some athletes whose performance sits outside the generalised trend, showing increased performance gains from additional concentric impulse about the level at which most individuals are deriving no further benefit (Figs. 2 and 3). Nevertheless, these findings tend to suggest that for male swimmers capable of producing greater than 230 N.s of impulse, it might be most beneficial for their strength and conditioning program to focus on improving their rate of force development, as it is possible that developing this high level of impulse in a shorter block time is required to further improve their swim start performance.

In contrast to the results for the male swimmers, which had concentric impulse as the sole contributing force-time variable from squat jumps, the swim start performance to 5 m and 15 m for females were also influenced by other factors such as RSImod, mean power and concentric RPD. A few possible explanations for the differing strategies could be attributed to maximal strength capacity, load-velocity and neuromuscular capability between both sexes. Although lower body muscular strength was not measured in the current study, maximal strength has been shown to be a limiting factor in jumping ability and other lower body measure of explosive strength (*Andersen & Aagaard, 2006*; *Suchomel et al., 2018*). Previous research has demonstrated that males possess greater maximal strength and ability to produce greater velocities at the same percentage of one repetition maximum than their female counterparts (*Sole et al., 2018*; *Torrejon et al., 2019*). When comparing the force-time curves in the countermovement jump between sexes, previous research has reported that the male and female differences in countermovement jump height were attributed to force characteristics and not temporal characteristics of the force-time curve (*Beckham et al., 2019*; *Sole et al., 2018*). This suggests that both sexes possess similar abilities to express forces, but the primary difference in jumping ability was due to the rate and magnitude of force production during both peak eccentric and concentric force production, which may be explained by differences in muscle architecture and structure, such as thickness and size of muscle fibers (*Laffaye, Wagner & Tombleson, 2014*). These sex related differences might therefore explain some of the differing swim start predictors identified in the present study.

Previous studies have suggested that there is a trade-off between time spent on the starting block and take-off velocity, as the likelihood of greater impulses being produced with greater block times (*Breed & McElroy, 2000*; *Takeda et al., 2017*; *Vantorre, Chollet & Seifert, 2014*). From a practical standpoint, a possible strategy to increase impulse generated on the starting block without excessively increasing the time of force application is to increase muscular strength and rate of force development qualities of the lower body through heavy resistance training, ballistic concentric-dominant exercises (i.e., jumps without a preceding eccentric contraction) and plyometric training (*Aagaard et al., 2002*; *West et al., 2011*). Heavy resistance training has been shown to increase power production, rate of power development, rate of force development and increases in muscle fiber cross-sectional area and neuromuscular activity (*Jakobsen et al., 2012*). Ballistic/plyometric training may improve the transfer of maximal strength to power production and rate of force development (*Suchomel et al., 2018*), thereby significantly improving swim start performance metrics including time to 5 m, take-off velocity and impulse (*Bishop et al., 2009*; *Rebutini et al., 2014*; *Rejman et al., 2017*). From a monitoring perspective, if a swimmer possesses the concentric impulse production required but has slow start times to 5 m and 15 m, improving rate force development and/or assessing technical factors such as angle of entry, degree of streamline, hydrodynamic drag and underwater propulsion may be imperative to maximise strength transfer to the swim start and ultimately swimming performance (*Vantorre, Chollet & Seifert, 2014*). Thus, swimmers should be concurrently performing lower body strength and conditioning program that includes some mixture of strength, ballistic and/or power training while ensuring sufficient practice of the swim start to optimise the transfer of their strength and conditioning program in improving swim start performance (*Breed & Young, 2003*).

There are some limitations in this study that could be addressed in future research. Firstly, baseline strength was not measured in any of the participants. Future work should examine the relationship between lower body force-time characteristics in strength matched swimmers and its effect on swim start performance to elucidate if differences between male and female swimmers were due to muscular strength or neuromuscular differences (*Nimphius, 2019*). Secondly, due to the difference in sample sizes for the different swim strokes in the current study, it would be worth exploring what force-time characteristics underpin swim start performance in other swim strokes in comparison to the front crawl, and if there are different neuromuscular qualities required for swim start performance in the different swim strokes.

CONCLUSION

In summary, this study has identified bodyweight squat jump concentric impulse as a key lower body force-time characteristic that was significantly related to swim start performance in high-performance swimmers. As impulse is the product of the ground reaction force and time of force application, it is integral for a swimmer to have the requisite ability to generate a high level of concentric impulse in a relatively short amount of time. Due to the different strength of the prediction equations, it appears that male and female swimmers utilise somewhat differing strategies during the swim start. While it is unknown if this is predominantly a result of the differences in muscular strength and force producing capacity between sexes, our results highlight the need for strength and conditioning coaches to consider individualising training programs to enhance swim start performance and ultimately swimming performance between sexes.

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Competing Interests

Justin Keogh is an Academic Editor for PeerJ.

Author Contributions

- Shiqi Thng conceived and designed the experiments, performed the experiments, analyzed the data, prepared figures and/or tables, authored or reviewed drafts of the paper, and approved the final draft.
- Simon Pearson conceived and designed the experiments, performed the experiments, analyzed the data, authored or reviewed drafts of the paper, and approved the final draft.
- Evelyne Rathbone analyzed the data, authored or reviewed drafts of the paper, and approved the final draft.
- Justin W.L. Keogh conceived and designed the experiments, analyzed the data, authored or reviewed drafts of the paper, and approved the final draft.

Human Ethics

The following information was supplied relating to ethical approvals (i.e., approving body and any reference numbers):

Ethical approval to conduct this study was attained from Bond University Human Research Ethics Committee (0000016006), The University of Queensland Human Research Ethics Committee (HMS17/41) and Swimming Australia Ltd.

Data Availability

The following information was supplied regarding data availability:

The raw data is available in the Supplementary Files.

Supplemental Information

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APPENDIX 8: DEFINITION OF SQUAT JUMP VARIABLES OBTAINED FROM THE FORCEDECKS FORCE PLATFORM (CHAPTER 4)

Variable	**Definition**
Concentric impulse [N.s.]	Net impulse of vertical force during the Concentric Phase
Concentric mean force [N]	Mean vertical force during the concentric phase
Concentric mean power [W]	Mean power during concentric phase
Concentric peak force [N]	Peak vertical force during the concentric phase
Concentric rate of power development (RPD) [W/s]	Rate of power development between start of concentric phase to peak power
Force at peak power [N]	Vertical force at moment of peak power
Peak power [W]	Maximum power in the concentric phase
Reactive strength index modified (RSImod) [m/s]	Jump height (Flight Time) divided by contraction time
Take-off peak force [N]	Maximum vertical force over from start of movement to take-off
Concentric peak velocity [m/s]	Peak velocity during concentric phase
Concentric rate of force development (RFD) BW [N/s/kg]	Rate of force development for vertical force during the concentric phase divided by body mass
Concentric RFD [N/s]	Rate of force development for vertical force during the concentric phase
Jump height (impulse-momentum) [cm]	Jump height calculated by taking velocity at the instant of take-off and predicting the maximum vertical displacement of the centre of mass based on body mass (measured in centimetres)
Velocity at peak power [m/s]	Velocity at peak power (from start of movement to take-off)

APPENDIX 9: ON-BLOCK MECHANISTIC DETERMINANTS OF START PERFORMANCE IN HIGH PERFORMANCE SWIMMERS – PUBLISHED VERSION

Thng S, Pearson S, Mitchell LJ, Meulenbroek C, Keogh JW. (2021). On-block mechanistic determinants of start performance in high performance swimmers. Sports Biomechanics. 3:1-13 DOI: 10.1080/14763141.2021.1887342

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APPENDIX 10: DEFINITION OF ON-BLOCK VARIABLES DERIVED FROM KISWIM (CHAPTER 5)

	Variable	**Definition**
Reaction time	Time to 1st move (s)	Time of the first movement when the absolute force differs from that at the gun by 0.1 x body mass
	1st move rear (s)	Time of the first movement on the rear force plate
	1st move grab (s)	Time of the first movement in resultant force on the grab bar
	1st move front (s)	Time of the first movement on the front force plate
Resulting movements (expressed as a percentage of block time)	Hands off (% BT)	The first time the vertical force on the grab bar is less than 2 % of body mass
	Toe off rear (% BT)	The first time the horizontal force on the grab bar is less than 2 % of body mass
On-block force application (all variables are expressed as per body mass)	Force horizontal peak	Peak horizontal force (grab bar component subtracted)
	Force vertical peak	Peak vertical force (grab bar component subtracted)
	Force resultant peak	Peak resultant force (grab bar component subtracted)
	Front horizontal peak	Peak horizontal force on the front plate (grab bar component not subtracted)
	Front vertical peak	Peak vertical force on the front plate (grab bar component not subtracted)

	Front resultant peak	Peak resultant force on the front plate (grab bar component not subtracted)
	Front resultant average	Average resultant force on the front plate (grab bar component not subtracted)
	Rear horizontal peak	Peak horizontal force on the foot plate (Grab bar component not subtracted)
	Rear vertical peak	Peak vertical force on the foot plate (Grab bar component not subtracted)
	Rear resultant peak	Peak resultant force on the foot plate (Grab bar component not subtracted)
	Rear resultant average	Average resultant force on the foot plate (Grab bar component not subtracted)
	Grab resultant average	Average grab bar resultant force
	Grab resultant peak	Peak grab bar resultant force
	Peak power (W/kg)	Peak power from gun to leaving the blocks
Timing of on-block force application (all variables are expressed as a percentage of block time)	Horizontal peak force	Time of horizontal peak horizontal force (grab bar component subtracted)
	Vertical peak force	Time of peak vertical force (grab bar component subtracted)
	Resultant peak force	Time of peak resultant force (grab bar component subtracted)
	Rear horizontal peak force	Time of peak horizontal force on the foot plate (grab bar not subtracted)

	Rear vertical peak force	Time of peak vertical force on the foot plate (grab bar not subtracted)
	Rear resultant peak force	Time of peak resultant force on the foot plate (grab bar not subtracted)
	Front horizontal peak force	Time of peak horizontal force on the front plate (grab bar not subtracted)
	Front vertical peak force	Time of peak vertical force on the front plate (grab bar not subtracted)
	Front resultant peak force	Time of peak resultant force on the front plate (grab bar not subtracted)
	Grab resultant peak force	Time of peak resultant force on the grab bar
	Peak power	Time of peak power from gun to leaving the blocks
On-block outcome kinetics and kinematics	Average power (W/kg)	Average power from gun to leaving the blocks
	Work/kg (joules)	Average power*seconds from gun to take-off
	Horizontal take-off velocity (m/s)	Integrated horizontal acceleration from start gun to take-off
	Average acceleration (m/s/s)	Take-off horizontal velocity divided by seconds from gun to take-off
	Resultant average force	Average resultant force i.e. $\sqrt{}$vertforce^2 + horforce^2 (grab bar component subtracted)
	Vertical take-off velocity (m/s)	Integrated vertical acceleration from start gun to take-off, then integrate

		acceleration from start gun to off-block
	Resultant take-off velocity (m/s)	Resultant take-off velocity
	Take-off angle (°)	Take-off angle of swimmer
Performance times	Time to 5 m, 7.5 m, 10 m, 15 m (s)	Time from starting signal till the centre of the swimmer's head passes the respective distance

APPENDIX 11: PUSHING UP OR PUSHING OUT – AN INITIAL INVESTIGATION INTO HORIZONTAL- VERSUS VERTICAL-FORCE TRAINING ON SWIMMING START PERFORMANCE: A PILOT STUDY – PUBLISHED VERSION

Pushing up or pushing out—an initial investigation into horizontal- versus vertical-force training on swimming start performance: a pilot study

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ABSTRACT

Background: The block phase in the swimming start requires a quick reaction to the starting signal and a large take-off velocity that is primarily horizontal in direction. Due to the principle of specificity of training, there is a potential benefit of performing a greater proportion of horizontal force production exercises in a swimmers' dry-land resistance training sessions. Therefore, the purpose of this pilot study was to provide an insight into the effects of a horizontal- (HF) vs vertical-force (VF) training intervention on swim start performance.

Methods: Eleven competitive swimmers (six males (age 20.9 ± 1.8 years, body mass 77.3 ± 9.7 kg, height 1.78 ± 0.05 m) and five females (age 21.4 ± 2.0 years, body mass 67.5 ± 7.4 kg, height 1.69 ± 0.05 m)) completed 2 weekly sessions of either a horizontal- or vertical-force focused resistance training programme for 8 weeks. Squat jump force-time characteristics and swim start kinetic and kinematic parameters were collected pre- and post-intervention.

Results: Across the study duration, the swimmers completed an average of nine swimming sessions per week with an average weekly swim volume of 45.5 ± 17.7 km (HF group) and 53 ± 20.0 km (VF group), but little practice of the swim start per week ($n = 9$). Within-group analyses indicated a significant increase in predicted one repetition maximum (1RM) hip thrust strength in the HF group, as well as significant increases in grab resultant peak force but reductions in resultant peak force of the block phase for the VF group. No significant between-group differences in predicted 1RM hip thrust and back squat strength, squat jump force-time and swim start performance measures were observed after 8 weeks of training. Significant correlations in the change scores of five block kinetic variables to time to 5 m were observed, whereby increased block kinetic outputs were associated with a reduced time to 5 m. This may be indicative of individual responses to the different training programmes.

Discussion: The results of this current study have been unable to determine whether a horizontal- or vertical-force training programme enhances swim start performance

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after an 8-week training intervention. Some reasons for the lack of within and between group effects may reflect the large volume of concurrent training and the relative lack of any deliberate practice of the swim start. Larger samples and longer training duration may be required to determine whether significant differences occur between these training approaches. Such research should also look to investigate how a reduction in the concurrent training loads and/or an increase in the deliberate practice of the swim start may influence the potential changes in swim start performance.

Subjects Kinesiology, Orthopedics
Keywords Swim start, Swimming, Specificity of training, Force-vector theory, Resistance training

INTRODUCTION

The important role that muscular strength and power play in enhancing swimming performance has led to the widespread adoption of dry-land resistance training modalities into a concurrent training model for competitive swimmers (*Aspenes et al., 2009*; *Crowley, Harrison & Lyons, 2017*; *Haycraft & Robertson, 2015*). While much of the swimming strength and conditioning research has been on the free swim portion (*Crowley, Harrison & Lyons, 2017*), there is now a greater focus on starts and turns since swimmers have to rapidly apply large forces on the starting block or wall to increase horizontal impulse and velocity (*Born et al., 2020*; *Jones et al., 2018*; *Rebutini et al., 2014*).

Changes in the starting block and starting technique may have further increased the importance of lower body strength and power for swim start performance. The OSB11 start block, which was introduced by the International Swimming Federation in 2010, has an angled kick plate at the rear of the block that enables the swimmer to adopt a kick start technique (*Tor, Pease & Ball, 2015a*). The additional kick plate allows for an increased duration of effective force application (i.e. greater horizontal force component) on the blocks, which can increase horizontal impulse and take-off velocity (*Honda et al., 2010*).

With the new OSB11 start block and kick start technique, the swim start may share some similarities to the sprint start in track and field regarding the starting position, importance of a quick reaction to the starting stimulus, and the need to produce large horizontal impulse on the starting blocks (*Čoh et al., 2017*; *Harland & Steele, 1997*). Analysis of the force-time characteristics of swimmers performing the squat jump has identified concentric impulse as a strong predictor of swim start performance as assessed by time to 5 m and 15 m (*Thng et al., 2020*). Further, near perfect correlations ($r > 0.90$) between countermovement jump height or take-off velocity and very large correlations for measures of maximal strength ($r = 0.7–0.9$) to swim start performance have been reported in a recent systematic review (*Thng, Pearson & Keogh, 2019*).

Despite the strength of this cross-sectional literature (*Thng, Pearson & Keogh, 2019*), there is relatively little research quantifying the chronic effects of resistance training on swim start performance. Three studies have utilised jump and plyometric exercise programmes (*Bishop et al., 2009*; *Rebutini et al., 2014*; *Rejman et al., 2017*), two studies (*Breed & Young, 2003*; *Garcia-Ramos et al., 2016*) used a more general resistance training programme, and one study (Born et al., 2020) compared the effects of maximal strength resistance training to plyometrics. The three plyometric studies included adolescent (Bishop et al., 2009) and national level swimmers (Rebutini et al., 2014; Rejman et al., 2017) who performed 6–9 weeks of plyometrics, twice a week. Significant improvements in time to 5 m and 5.5 m, take-off velocity, horizontal forces and impulse were observed as a result of these plyometric exercise programmes (Bishop et al., 2009; Rebutini et al., 2014; Rejman et al., 2017). In contrast, the remainder of these plyometric and resistance training studies typically reported no significant changes in time to 5 m or 15 m, or any block phase kinetic or kinematic characteristics (Born et al., 2020; Breed & Young, 2003; Garcia-Ramos et al., 2016). The only exception to this was the significant improvements in time to 5 m and 15 m observed for the subset of under 17-year-old swimmers who performed maximal strength training, with no such effects reported for the under 17-year-old plyometric group (Born et al., 2020).

A possible explanation for the uncertainty regarding whether jump/plyometric or more general resistance training programmes produces greater improvements in swim start performance may reflect the direction-specific nature of resistance training. In a review by Randell et al. (2010) on the specificity of resistance training to sports performance, it was proposed training adaptations may be direction-specific, and that athletes who are required to apply forces in the horizontal plane should perform several exercises containing a horizontal component. More recently, this directional specificity of training has been referred to as the force-vector theory (Fitzpatrick, Cimadoro & Cleather, 2019), with the hip thrust and prowler push/heavy sled pull being two of the most commonly used horizontal-force exercises (Contreras et al., 2017; Fitzpatrick, Cimadoro & Cleather, 2019; Morin et al., 2017; Winwood et al., 2015). A study by Contreras et al. (2017) using the hip thrust significantly improved 10 m and 20 m sprint running times (−1.05% and −1.67%, respectively) compared to the front squat, which is a vertical-force exercise (+0.10% and −0.66%, respectively). The prowler push, which requires the athlete to push a loaded sled in the horizontal plane, has been shown to closely mimic the horizontal plane power requirements of sprinting (Tano et al., 2016). A study involving 30 sub-elite rugby players observed that a horizontal-focused resistance training programme including the prowler push significantly improved performance in a number of strength, sprinting, and change of direction tests (Winwood et al., 2015). However, no significant between-group effects were observed between the horizontal-focused and traditional resistance training programmes (Winwood et al., 2015).

The potential direction specificity of resistance training exercises for improving aspects of swim start performance has been examined in two jump and plyometric training studies (Rebutini et al., 2014; Rejman et al., 2017) and two acute training studies utilising post-activation potentiation (PAP) (Cuenca-Fernandez, Lopez-Contreras & Arellano, 2015; Cuenca-Fernández et al., 2018). Rebutini et al. (2014) and Rejman et al. (2017) observed a 10.4% and 13.8% increase in take-off velocity in the swim start post 9- and 6-weeks of plyometric training, respectively, that included a variety of horizontal jumps. Acute improvements in time to 5 m (Cuenca-Fernandez, Lopez-Contreras & Arellano, 2015; Cuenca-Fernández et al., 2018) and 15 m (Cuenca-Fernandez, Lopez-Contreras & Arellano, 2015) after performing PAP protocols that were biomechanically similar to the foot position in the kick start on the OSB11 start block have also been observed. However, out of these four plyometric and PAP studies, only one (*Cuenca-Fernandez, Lopez-Contreras & Arellano, 2015*) utilised the OSB11 start block and the kick start technique currently used by high performance swimmers.

Therefore, the primary aim of this pilot study was to gain some preliminary insight into the comparative effects of a horizontal- vs vertical-force resistance training programme on swim start performance and squat jump (SJ) force-time characteristics. A secondary aim of the study was to better understand how changes in certain SJ force-time characteristics may be correlated with the changes in swim start performance in competitive swimmers.

MATERIALS AND METHODS

Experimental design

An 8-week training programme sought to examine how a horizontal-force (HF) compared to vertical-force (VF) oriented emphasis resistance training programme would potentially alter swim start performance. Participants were randomly assigned to either a HF or VF training group (HF: $n = 6$, VF: $n = 7$), with each group performing two resistance training sessions per week.

Participants

Thirteen participants (8 males (age 21.0 ± 1.6 years, body mass 78.6 ± 8.3 kg, height 1.80 ± 0.06 m), and 5 females (age 21.4 ± 2.0 years, body mass 67.5 ± 7.4 kg, height 1.69 ± 0.05 m)) volunteered to participate in this study. Participants were national level swimmers with at least 4 years' experience in competing in national championships and at least 1 year of land-based resistance training experience that included the barbell back squat and hip thrust under the supervision of a strength and conditioning coach. Participants with any known contraindication to maximal training performance and/or injuries that would interfere with their ability to complete the study or compromise their health and wellness were excluded. Prior to participating in this study, participants were briefed on the experimental design and gave written informed consent to participate in the study. This investigation was conducted in accordance with the Declaration of Helsinki and approved by Bond University Human Research Ethics Committee (00088).

Assessments were conducted at baseline (week one) and the end of the training programme (week nine). Participants were instructed to maintain their nutritional and sleep habits, and to avoid alcohol and caffeine consumption for at least 24 h before testing sessions. All tests were performed on the same day of the week between 7:00 am and 11:00 am. Participants reported to the gymnasium to perform the squat jump test prior to the swim start performance test.

Training intervention

The training programme was organised into two phases. In the first phase (weeks one to four), each group performed three HF and VF lower body exercises, respectively.

Table 1 **An outline of the 8-week intervention programme for the Horizontal-Force (HF; $n = 6$) and Vertical-Force (VF; $n = 5$) training group with weekly sets, repetition, and load progression for the lower body strength and jumping exercises.**

Intervention Group	Day	Exercise	Training focus							
			Strength				Strength-power			
			Training week							
			1	2	3	4	5	6	7	8
			Sets × reps	Sets × reps	Sets × reps	Sets × reps	Sets × reps	Sets × reps	Sets × reps	Sets × reps
HF group	1a	Barbell hip thrust	3 × 8	3 × 8	3 × 6	2 × 6	3 × 5	3 × 5	3 × 4	2 × 4
	1b	'Start' jump					3 × 3	3 × 3	3 × 3	2 × 3
	2a	Prowler push^	3 × 8	3 × 8	3 × 6	2 × 6	3 × 5	3 × 5	3 × 4	2 × 4
	2b	Drop vertical jump					3 × 3	3 × 3	3 × 3	2 × 3
VF group	1a	Back squat	3 × 8	3 × 8	3 × 6	2 × 6	3 × 5	3 × 5	3 × 4	2 × 4
	1b	Squat jump					3 × 3	3 × 3	3 × 3	2 × 3
	2a	Rear foot elevated split squat^	3 × 8	3 × 8	3 × 6	2 × 6	3 × 5	3 × 5	3 × 4	2 × 4
	2b	Drop vertical jump					3 × 3	3 × 3	3 × 3	2 × 3

Note:
^ Repetitions listed are for each leg.

A direction specific lower body jump was added in the second phase for each group (weeks five to eight) (Table 1). The HF training group was prescribed a 'start jump' which is a jump for horizontal distance initiated from a mimicked swim start position (Fig. 1), while the VF training group performed the squat jump. When performing the jumps, the HF group were instructed to jump as far forward as possible, while the VF group were instructed to jump as high as possible with each jump.

Participants performed the training programme utilising sets and repetition ranges typically used for developing maximal strength (*Bird, Tarpenning & Marino, 2005*). Participants followed two 4-week mesocycles using a 3:1 loading paradigm, with a progressive increase in load for the first 3 weeks followed by a reduction in load in the fourth week (*Turner, 2011*). This was considered important as the swimmers were still maintaining high volumes of swimming training throughout the intervention. As the majority of propulsive forces in the free swim phase comes from the upper body (*Morouço et al., 2015*), both groups also performed three sets of several upper body exercises including pull-ups, bench pull or seated row; and three sets of exercises for the abdominals/lower back region, as successfully used by *Contreras et al. (2017)* in a previous horizontal- vs vertical-force direction study. Sets were separated by a 1-min rest period (*Ritchie et al., 2020*). Training records were kept for each participant to analyse the load progression of the training programme. Predicted one repetition maximum (1RM) of the hip thrust and barbell back squat was calculated pre- and post-intervention using the Brzycki equation: Predicted 1RM = weight lifted/1.0278–0.0278 (no. of repetitions) (*Brzycki, 1993*). Repetition ranges used in the predicted 1RM was performed during the first training session (estimated from eight repetitions) and at the last training session

Figure 1 **Initial positioning of the 'start' jump for the Horizontal-Force (HF) training group.**
Full-size DOI: 10.7717/peerj.10937/fig-1

(estimated from four repetitions). Participants were asked to refrain from performing any additional resistance training and to maintain their current diet for the course of this study.

Squat jump test

The SJ test was collected as previously described by *Thng et al. (2020)*. All participants completed a standardised dynamic warm-up consisting of a predetermined series of dynamic joint ranges of motion of the upper and lower body under the supervision of a strength and conditioning coach. Participants were then given two practice SJs before the test was conducted. All SJs were performed on a force platform (FD4000; ForceDecks, London, United Kingdom), with a sample rate of 1,000 Hz. Participants started in an upright standing position with their hands on their hips and were instructed to keep their hands on their hips to prevent the influence of any arm movements for the jump trials. All participants were instructed to adopt a squat position using a self-selected depth that was held for 3 seconds before attempting to jump as high as possible (*Mitchell et al., 2017*). A successful trial was one that did not display any small amplitude countermovement at the start of the jump phase on the force trace (*Sheppard & Doyle, 2008*). All participants performed three maximal effort SJs with a 30-s passive rest between each effort. The SJ trial with the highest jump height was kept for data analysis. Jump height was determined by the flight-time method (Jump height = $g^{*}t^{2}/8$, where g is the

Table 2 **Description of squat jump variables obtained from the ForceDecks force platform, and the swim start variables obtained from the KiSwim Performance Analysis System.**

	Variable	Description
ForceDecks SJ variables	Concentric impulse (N.s.)	Net impulse of vertical force during the concentric phase
	Concentric mean power (W)	Mean power during concentric phase
	Concentric rate of power development (RPD) (W/s)	Rate of power development between start of concentric phase to peak power
	Jump height (cm)	Jump height calculated from Flight Time (time between take-off and landing) in centimetres
	Reactive strength index modified (RSImod) (m/s)	Jump height (Flight Time) divided by contraction time
KiSwim swim start kinetic variables	Average acceleration (m/s/s)	Horizontal take-off velocity/seconds from starting gun to take-off
	Average power (W/kg)	The average power relative to the swimmers' body mass produced from the starting signal to when the swimmer leaves the starting block. This was calculated as the product of (absolute force × absolute velocity)/body mass
	Horizontal take-off velocity (m/s)	The horizontal take-off velocity calculated by integrating horizontal acceleration
	Work/kg (J/kg)	Average power × seconds from the starting gun to take-off
	Front horizontal peak force (N)	Peak horizontal force on the front plate of the starting block (grab bar component not subtracted)
	Grab resultant peak force (N/BW)	Peak grab bar resultant force
	Rear horizontal peak force (N)	Peak horizontal force on the foot plate (grab bar component not subtracted)
	Total resultant peak force (N)	Peak resultant force (grab bar component subtracted)
	Rear resultant average force (N/BW)	Average resultant force on the foot plate (grab bar component not subtracted)
Swim start performance times	Time to 5 m and 15 m (s)	Time from the starting signal to a swimmers' head crossing the 5 m and 15 m mark. This is digitised at the point where the centre of the swimmers' head crosses 5 m and 15 m

acceleration due to gravity and *t* is the flight time) (*Linthorne, 2001*). Ground reaction force data from the SJs were analysed using the commercially available ForceDecks software (ForceDecks, London, United Kingdom). A description of the SJ variables that were identified by *Thng et al. (2020)* as significant predictors of swim start performance were extracted for analysis are provided in Table 2.

Swim start performance test

Swim starts were collected using methods as described by *Thng et al. (2020)*. Prior to the swim start test, all swimmers completed a pool-based warm-up based on their usual pre-race warm-up routine. Participants then performed three maximal effort swim starts to 15 m with their main swim stroke (front crawl (n = 8), butterfly (n = 3), or breaststroke (n = 2)) and preferred kick plate position, which was recorded to ensure consistency between testing sessions. Trials were started as per competition conditions and swimmers were instructed to swim to a distance past the 15 m mark, in order to ensure that representative values at the 15 m distance were obtained (*Barlow et al., 2014*). Two-minutes of passive recovery were given between each trial (*Tor, Pease & Ball, 2015b*). The start with the fastest 15 m time was selected for further analysis. Swim starts were collected using a Kistler Performance Analysis System—Swimming (KiSwim, Kistler Winterthur, Switzerland), which utilises a force instrumented starting block, constructed to match the dimensions of the Omega OSB11 block (KiSwim Type 9691A1; Kistler Winterthur, Switzerland). Time to 5 m and 15 m were collected using five calibrated high speed digital cameras operating at 100 frames per second, synchronised to the instrumented KiSwim starting block. One camera was positioned 0.95 m above the water and 2.5 m perpendicular to the direction of travel to capture the start and entry of swimmer into the water, while the other three cameras were positioned 1.3 m underwater at 5 m, 10 m and 15 m perpendicular to the swimmer to capture the time to 15 m. The times to 5 m and 15 m were defined as the time elapsed from the starting signal until the apex of the swimmer's head passed the respective distances (*Tor, Pease & Ball, 2015b*). An Infinity Start System (Colorado Time Systems, Loveland, CO, USA) provided an audible starting signal to the athletes and an electronic start trigger to the KiSwim system. Kinetic and kinematic variables of block performance extracted for analysis were identified by *Thng et al. (2020)* as key predictors of time to 5 m and 15 m (Thng et al., 2021, unpublished data). A description of the swim start variables analysed are provided in Table 2.

Statistical analysis

Descriptive statistics are reported as mean ± SD for normally distributed continuous variables and frequencies for categorical variables. Normality was checked using histograms, normal Q–Q plots, and the Shapiro–Wilk test. A paired sample *t*-test was used to determine whether statistically significant differences were found between pre- and post-test means within each group. Independent *t*-tests were carried out to test for the difference in change in the outcome between intervention groups. Effect sizes (ES) with 95% confidence intervals (95% CI) were reported in standardised (Cohen's d) units as the change in mean to quantify the magnitude of differences within (i.e. post-intervention—pre-intervention results) and between the two intervention groups (i.e. HF and VF). Criteria to assess the magnitude of observed changes were: 0.0–0.2 trivial; 0.20–0.60 small; 0.60–1.20 moderate; and >1.20 large (*Hopkins, 2002*). Effect sizes were calculated using a programme created by *Lenhard & Lenhard (2016)*.

To gain some preliminary insight into how changes in the SJ force-time characteristics may be correlated with the changes in swim start performance, the association between the change scores (calculated as the difference between each individuals' pre- and post-test scores) for these outcomes were assessed by Pearson's product-moment correlation coefficient (r). Data were analysed with SPSS version 23.0.0 (SPSS Inc., Chicago, IL, USA). P-values < 0.05 were deemed to indicate statistical significance.

RESULTS

Training compliance

Of the 13 initial participants, 11 participants completed the training study (Table 3). Two participants were removed due to moving to another swim squad ($n = 1$) and non-adherence to the training protocol ($n = 1$). Participants completed a total of 14 ± 3 out

Table 3 Physical characteristics of participants ($N = 11$).

Variables	HF group ($n = 6$)	VF group ($n = 5$)
Age (years)	21.3 ± 1.7	21.0 ± 2.2
Sex (male/female)	3/3	3/2
Body mass (kg)	74.3 ± 10.5	70.0 ± 10.3
Height (m)	1.73 ± 0.06	1.74 ± 0.08
Weekly in-water training volume (km)	45.5 ± 17.7	53.0 ± 20.0
Weekly number of swim starts performed	9 ± 2	9 ± 2

Note:
All data, apart from the sex of the participants are presented as means and standard deviations.

of 16 training sessions, with the primary reasons for missed training sessions being short-term illness or domestic competitions. A summary of the within-group and between-group changes are provided in Table 4.

Within-group changes post-intervention

Only three significant within-group differences were observed across both groups. For the HF group, a significant increase in predicted 1RM hip thrust strength ($p = 0.04$) was observed. The VF group had a significant increase in KiSwim grab resultant peak force ($p = 0.007$) and a significant decrease in KiSwim resultant peak force ($p = 0.02$).

Between-group changes post-intervention

A greater increase in predicted 1RM strength for the hip thrust was observed in the HF training group (50%) than the increase in back squat strength for the VF training group (18%) after 8 weeks of training (ES = 1.36). Moderate effect sizes were observed in two SJ force-time variables and five KiSwim variables (Table 4). Specifically, moderate effect size improvements in SJ jump height and three swim start kinetic measures were observed in the HF group. In the VF group, SJ concentric RPD and two swim start kinetic measures favoured moderate effect size improvements in the VF group.

When looking at individual changes across both groups, no significant correlations were observed between the change scores in any of the ForceDecks outcome measures and time to 5 m or 15 m. Similarly, there were no significant correlations in the change score correlations between the KiSwim outcomes and time to 15 m. However, significant correlations between the change scores for five KiSwim outcomes and time to 5 m were observed. These were average acceleration ($r = -0.82$, $p = 0.02$), horizontal take-off velocity ($r = -0.81$, $p = 0.03$), average power ($r = -0.77$, $p = 0.05$), work ($r = -0.74$, $p = 0.01$) and rear resultant average force ($r = -0.71$, $p = 0.02$).

DISCUSSION

The present pilot study was designed to provide some insight into the potential directional specificity of resistance training (now referred to as the force-vector theory) on swim start performance and squat jump (SJ) force-time characteristics in competitive swimmers. This was achieved by examining the within- and between-group training-related changes in swim start performance for two groups of competitive swimmers, who differed on

Table 4 **Pre- (week 1) and post- (week 9) measures of squat jump force-time variables and swim start kinetic and kinematic parameters for the horizontal-force (HF) and vertical-force (VF) training groups.** Results are presented as mean ± SD except for effect sizes and change scores.

	HF group (n = 6)				VF group (n = 5)				Between-group differences	
	Week 1	Week 9	Change scores	Within-group ES (95% CI)	Week 1	Week 9	Change scores	Within-group ES (95% CI)	Mean difference (95% CI)	ES (95% CI)
Predicted 1RM strength										
Hip thrust (kg)	78.5 ± 15.0	118.3 ± 26.9	39.8 ± 16.6[**]	**1.83 [−0.08 to 3.73]**						
Barbell back squat (kg)					70.6 ± 27.0	85.20 ± 38.67	14.6 ± 20.8	0.44 [−1.34 to 2.21]	25.23 [−0.23 to 50.70]	**1.36 [0.04–2.67]**
SJ force-time variables										
Jump height (cm)	28.4 ± 7.5	29.1 ± 7.0	0.8 ± 3.1	0.11 [−1.50 to 1.71]	29.0 ± 10.7	27.1 ± 8.3	−1.9 ± 2.9	−0.19 [−1.95 to 1.56]	2.63 [−1.50 to 6.76]	**0.87** [−0.37 to 2.11]
Concentric impulse (N.s.)	183.2 ± 46.2	182.3 ± 49.4	−0.9 ± 7.6	−0.02 [−1.62 to 1.58]	167.3 ± 43.3	165.3 ± 44.1	−2.0 ± 8.4	−0.05 [−1.80 to 1.71]	1.06 [−9.84 to 11.97]	0.14 [−1.05 to 1.33]
RSImod (m/s)	0.79 ± 0.16	0.73 ± 0.21	−0.07 ± 0.10	−0.32 [−1.93 to 1.29]	0.75 ± 0.30	0.73 ± 0.33	−0.02 ± 0.14	−0.06 [−1.82 to 1.69]	−0.04 [−0.20 to 0.12]	−0.42 [−1.62 to 0.78]
Concentric mean power (W)	1414.2 ± 387.6	1442.0 ± 527.8	27.8 ± 174.6	0.06 [−1.54 to 1.66]	1268.0 ± 437.5	1241.0 ± 587.7	−27.0 ± 254.8	−0.05 [−1.81 to 1.70]	54.8 [−238.3 to 347.9]	0.26 [−0.94 to 1.45]
Concentric RPD (W/s)	11986.3 ± 2879.3	10130.6 ± 3817.3	−1,855.6 ± 1921.3	−0.55 [−2.18 to 1.08]	10216.0 ± 5333.5	10874.5 ± 6109.3	658.4 ± 3017.4	0.12 [−1.64 to 1.87]	−2,514.1 [−5896.6 to 868.3]	**−1.02 [−2.28 to 0.24]**
KiSwim kinetic variables										
Average Power (W/kg)	19.66 ± 3.33	19.52 ± 2.94	−0.15 ± 0.63	−0.05 [−1.65 to 1.56]	20.65 ± 5.42	19.91 ± 5.05	−0.74 ± 0.97	−0.14 [−1.90 to 1.61]	0.59 [−0.50 to 1.68]	**0.74 [−0.49 to 1.97]**
Average Acceleration (m/s/s)	6.20 ± 0.80	6.15 ± 0.64	−0.04 ± 0.22	−0.07 [−1.67 to 1.53]	6.42 ± 1.14	6.26 ± 1.04	−0.16 ± 0.26	−0.15 [−1.90 to 1.61]	0.12 [−0.21 to 0.45]	0.50 [−0.70 to 1.71]
Work/kg (joules)	13.83 ± 2.00	13.91 ± 1.93	0.08 ± 0.43	0.04 [−1.56 to 1.64]	13.73 ± 2.68	13.57 ± 2.51	−0.16 ± 0.39	−0.06 [−1.82 to 1.69]	0.24 [−0.32 to 0.80]	0.58 [−0.63 to 1.79]
Horizontal take-off velocity (m/s)	4.36 ± 0.38	4.38 ± 0.36	0.03 ± 0.14	0.05 [−1.55 to 1.66]	4.29 ± 0.46	4.29 ± 0.41	0.00 ± 0.09	0.00 [−1.75 to 1.75]	0.03 [−0.13 to 0.19]	0.25 [−0.94 to −1.44]
Total resultant peak force (N/BW)	1.73 ± 0.21	1.68 ± 0.19	−0.05 ± 0.07	−0.25 [−1.86 to 1.36]	1.95 ± 0.53	1.84 ± 0.55	−0.11 ± 0.06[*]	−0.20 [−1.96 to 1.55]	−0.06 [−0.15 to 0.03]	**0.91 [−0.33 to 2.16]**
Front horizontal peak force (N/BW)	0.69 ± 0.07	0.70 ± 0.05	0.02 ± 0.05	0.16 [−1.44 to 1.77]	0.73 ± 0.05	0.72 ± 0.09	−0.01 ± 0.05	−0.14 [−1.89 to 1.62]	−0.03 [−0.09 to 0.04]	**0.60 [−0.61 to 1.81]**
Rear horizontal peak force (N/BW)	0.90 ± 0.19	0.88 ± 0.16	−0.02 ± 0.05	−0.11 [−1.72 to 1.49]	0.91 ± 0.16	0.92 ± 0.15	0.01 ± 0.05	0.06 [−1.69 to 1.82]	0.03 [−0.03 to 0.10]	**−0.60 [−1.81 to 0.61]**
Rear resultant average force (N/BW)	0.58 ± 0.10	0.58 ± 0.09	−0.01 ± 0.03	0.00 [−1.60 to 1.60]	0.58 ± 0.13	0.57 ± 0.13	−0.01 ± 0.03	−0.08 [−1.83 to 1.68]	0.00 [−0.04 to 0.04]	0.00 [−1.19 to 1.19]
Grab resultant peak force (N/BW)	38.67 ± 7.76	38.83 ± 7.65	0.17 ± 4.17	0.02 [−1.58 to 1.62]	36.20 ± 7.92	38.80 ± 8.26	2.60 ± 1.14[**]	0.32 [−1.44 to 2.09]	2.43 [−1.95 to 6.81]	**−0.76 [−1.99 to 0.47]**
Swim start performance times										
T5 m (s)	1.60 ± 0.15	1.61 ± 0.14	0.02 ± 0.03	0.07 [−1.53 to 1.67]	1.59 ± 0.19	1.61 ± 0.19	0.02 ± 0.03	0.11 [−1.65 to 1.86]	0.00 [−0.04 to 0.04]	0.00 [−1.19 to 1.19]
T15 m (s)	7.33 ± 0.69	7.32 ± 0.57	−0.01 ± 0.19	−0.02 [−1.62 to 1.59]	6.82 ± 0.91	6.85 ± 0.88	0.04 ± 0.08	0.03 [−1.72 to 1.79]	−0.04 [−0.28 to 0.19]	−0.33 [−1.53 to 0.86]

Notes:

[*] $p < 0.05$.

[**] $p < 0.01$.

BW, bodyweight; 95% CI, confidence interval of the differences within and between measures; ES, effect size; RPD, rate of power development; SD, standard deviation; SJ, squat jump.

For within group effects, a positive change score and effect size indicated that the post test score was larger than the pre-test score. For between group effects, a positive effect size indicated that the HF group had a larger change than the VF group.

Bolded values indicate an effect size difference of moderate or large.

whether they performed a horizontal- or vertical-force oriented emphasis resistance training programme.

Relatively few significant within-group changes in any outcome measures were observed, with the non-significant changes being trivial to small in their effect sizes. The three significant within-group changes included significant increases in predicted 1RM hip thrust strength for the HF group as well as significant increases in swim start grab resultant peak force but reductions in resultant peak force for the VF group. No significant between-group differences were observed between the HF and VF groups in predicted 1RM strength, SJ force-time and swim start performance measures post-intervention. However, seven moderate between-group effect size differences were observed, with four outcome measures favouring greater improvements for the HF group and three outcome measures favouring the VF group. As such, this current study has been unable to determine whether the inclusion of horizontally oriented exercises has any clear benefit to swim start performance over more conventional vertically oriented exercises.

Possible explanations for our lack of significant within- or between-group improvements may include the small number of participants and short duration of the training intervention, inclusion of plyometric and non-plyometric jumps in only the last four of 8 weeks of training, the interference effect due to concurrent training and the relative complexity of the swim start. Regarding the length of the intervention, the absence of any significant improvements in swim start performance in the current study was consistent with some studies involving 21 (*Born et al., 2020*) or 23 (*Breed & Young, 2003*) participants performing 6–8 weeks of resistance training, but inconsistent with other plyometric training studies of 6–9 weeks involving nine (*Rejman et al., 2017*), 10 (*Rebutini et al., 2014*) or 22 (*Bishop et al., 2009*) participants.

The potentially greater adaptations in swim start performance observed in previous plyometric studies may reflect the between study differences in plyometrics training volume. The present study only included 33 jumps, compared to previous successful plyometric studies (*Bishop et al., 2009*; *Rebutini et al., 2014*; *Rejman et al., 2017*), which included ~484–883 jumps across the study. Interestingly, even though *Born et al. (2020)* included comparable volumes of plyometrics in their training study (~360–588 jumps) to those of the successful studies, the plyometric training group reported no significant improvements in swim start performance. While it cannot be discounted that the present study included an insufficient volume of plyometric exercise, the lack of any widespread changes in lower body force-time characteristics and swim start performance metrics observed in the present study and some of the literature (*Born et al., 2020*; *Breed & Young, 2003*), may be indicative of the challenges coaches face in making any substantial improvements in strength and power characteristics that transfer to improved sporting performance within such short periods of concurrent training.

Concurrent training is complex in that both swim training and resistance training impose different acute stresses on the body that elicit distinct adaptations. In particular, the concurrent development of both muscular strength/power and aerobic endurance from resistance training and swimming training respectively can lead to conflicting neuromuscular adaptations (*Garcia-Pallares et al., 2009*). In the current study, participants were primarily middle to long distance swimmers, who performed nine in-water sessions weekly (HF: 45.5 ± 17.7 km and VF: 53 ± 20.0 km per week). The sessions had an average swimming volume of 5.1 km and 5.8 km for the HF and VF group per session, with two swimming sessions a day performed several days per week. In contrast, the resistance training programme was only performed twice per week. The interference effect from concurrent training is more likely observed with ≥ three sessions of high volume endurance training weekly (*Bishop et al., 2019*). Therefore, the high aerobic training volume for the participants in the present study likely attenuated any resistance training-induced adaptations. Consistent with this view, *Haycraft & Robertson (2015)* recommend swim training volumes be reduced ≤5 km per day to enable maximal strength and power gains and minimise neuromuscular fatigue.

It should also be acknowledged that the swim start is a discrete skill, requiring a quick reaction to the starting stimulus and the ability to effectively coordinate hand and foot forces to optimise horizontal impulse and take-off velocity. Unfortunately, the swimmers in the present study only performed a small number of swim starts per week (n = 9 ± 2), with this performed either during regular swim training or at the end of the session. It was also interesting to observe that *Born et al. (2020)* also reported a low volume of swim starts (n = 16) performed per week. *Breed & Young (2003)* emphasised that a higher skill component is involved in executing the swim start in comparison to vertical jump. This may reflect the requirement for how the ankle, knee, and hip joint moments needs to be coordinated effectively with those of the upper body during the block phase to maximise horizontal take-off velocity. Further, minimising the time to 15 m also requires a clean entry into the water and a streamlined glide position with undulatory leg kicks to minimise velocity loss while transitioning into the break-out of full swimming and stroking after 15 m (*Vantorre, Chollet & Seifert, 2014*). The relative absence of deliberate practice of the swim start coupled with performing the starts in a fatigued state may also help explain the minimal transfer of the resistance training interventions to improved swim start performance in the current study and that of *Born et al. (2020)*. However, significant correlations in the change scores of five block kinetic variables to time to 5 m were observed in the current study, whereby an increase in block kinetic variables was associated with a decrease in time to 5 m. Such correlations suggest that the longitudinal tracking of individual swimmers' SJ force-time characteristics may provide some insight into their potential improvements in swim start performance.

Due to the demands of competitive swimming, it seems necessary that a targeted approach of both resistance training and deliberate practice of the swim start is required across the annual periodisation plan to improve swim start performance. This is especially important to minimise the potential adverse effects of concurrent training and maximise skill acquisition, particularly for swimmers who need to improve aspects of their swim start technique, given the complexity of the swim start. Practical recommendations include a targeted block of resistance training focused on improving the strength and power characteristics required for the swim start in a low swimming volume phase such as pre-season for a longer duration than used in the present study. Specifically, extended intervention periods >6 months have been suggested for an optimal transfer of strength and power qualities to performance in well-trained endurance athletes (*Beattie et al., 2014*). Incorporating greater amounts of deliberate practice of swim starts, especially at the beginning of each training session when the swimmer is mentally and physically fresh would appear to be beneficial for skill acquisition (*Branscheidt et al., 2019*).

CONCLUSION

There were very few significant differences observed, either within or between the HF and VF groups after an 8-week training intervention on swim start performance. Despite exploring the inclusion of a higher proportion of horizontally oriented exercises based on the force-vector theory, the current study did not observe a transfer to improved swim start performance. However, this should not discount the potential value of including horizontally directed exercises to improve swim start performance, given the results were similar to those from more traditional vertically oriented exercises. Future studies should consider an extended training intervention completed during a phase of lower swim training volume to enable strength and power adaptions to occur.

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Justin W.L. Keogh is an Academic Editor for PeerJ.

Author Contributions

- Shiqi Thng conceived and designed the experiments, performed the experiments, analysed the data, prepared figures and/or tables, authored or reviewed drafts of the paper, and approved the final draft.

- Simon Pearson conceived and designed the experiments, performed the experiments, analysed the data, authored or reviewed drafts of the paper, and approved the final draft.
- Justin W.L. Keogh conceived and designed the experiments, analysed the data, authored or reviewed drafts of the paper, and approved the final draft.

Human Ethics

The following information was supplied relating to ethical approvals (i.e. approving body and any reference numbers):

Bond University Human Research Ethics Committee approved this research (00088).

Data Availability

The following information was supplied regarding data availability:

Raw data, including pre- and post-intervention measures of squat jump force-time measures and kinetic and kinematic variables of the swim start, are available as a Supplemental File.

Supplemental Information

Supplemental information for this article can be found online at http://dx.doi.org/10.7717/peerj.10937#supplemental-information.

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